

# A Feasibility Study: California Department of Forestry and Fire Protection Utilization of Infrared Technologies for Wildland Fire Suppression and Management Final Report

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August 15, 1990

Prepared for

Harold Walt, Director  
Department of Forestry and Fire Protection

George Deukmejian  
Governor  
State of California

Gordon K. Van Vleck  
Secretary for Resources  
The Resources Agency

by

Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California

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TECHNOLOGIES FOR WILDLAND FIRE SUPPRESSION  
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The study represents one phase of research performed at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the Department of Forestry and Fire Protection, State of California under a contract with the National Aeronautics and Space Administration.

## ABSTRACT

The National Aeronautics and Space Administration's Jet Propulsion Laboratory has completed a feasibility study using infrared technologies for wildland fire suppression and management. Sponsored by the Department of Forestry and Fire Protection, State of California, the study surveyed user needs, examined available technologies, matched the user needs with technologies, and defined an integrated infrared wildland fire-mapping concept system configuration. System component trade-offs were presented for evaluation in the concept system configuration. The economic benefits of using infrared technologies in fire suppression and management were examined. Follow-on concept system configuration development and implementation were proposed.



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## SECTION 1

### INTRODUCTION

In the summer of 1989, a feasibility study to examine the application of advanced infrared technology to wildland fire detection and mapping in the State of California was jointly initiated by the California Department of Forestry and Fire Protection (CDF) and the National Aeronautics and Space Administration's (NASA's) Jet Propulsion Laboratory (JPL). The objectives of this task were to understand the current and future user needs in infrared (IR) requirements for wildland fire management and to survey and identify what infrared technologies may be available to meet these needs. The results of that study are discussed in this report. In addition, to clearly present the mix of technology and needs, a "concept system configuration" is presented and discussed, and a plan for a more detailed follow-on conceptual design of the "concept system configuration" is presented.

#### 1.1 BACKGROUND

Thermal infrared sensing for forest fire detection and mapping has been under development by the Forest Service - United States Department of Agriculture (USDA) since the FIRESCAN Research Project began in 1962 (Hirsch, 1968). The original Forest Service airborne, infrared, line-scanning systems were stand-alone IR systems designed to produce hard copy images of the thermal characteristics of the terrain and fire, on board the aircraft. Timely delivery of the fire imagery to fire management personnel was a problem as the imagery was delivered either via drop tubes, conditions permitting, or hand delivered via ground transportation from the nearest airport.

The Fire Logistics Airborne Mapping Equipment (FLAME) project, a joint effort between the Forest Service and JPL, was charged with designing, developing, and implementing a modern, airborne, IR detection and mapping system with improved performance and flexibility over the original Forest Service systems (Enmark, 1984). The FLAME project upgraded the previous Forest Service sensor to provide increased spatial resolution, incorporation of human engineering, and real-time video display and storage. New detectors were installed to improve response time and data capture. All cabling was replaced and the controllers for the scanning unit were redesigned so that operator intervention was made easier. A new film recorder was integrated into the

system as was a video frame buffer. A video monitor was supplied to add the real-time display of the data.

In use today by the Forest Service are two airborne thermal IR surveillance and mapping systems, the JPL line scanner (FLAME) mounted in a Beechcraft King Air aircraft, and a modified Texas Instruments RS-7 scanner mounted in a Sweringen Merlin aircraft. The two systems are based at the Boise Interagency Fire Center (BIFC) in Boise, Idaho and are available for use on a nationwide basis to government agencies that request fire mapping and detection missions. Participating government agencies that use the systems include the United States Department of the Interior (USDI), Bureau of Land Management (BLM), Bureau of Indian Affairs (BIA), National Park Service (NPS), natural resource agencies in Canada, as well as the CDF.

Since the late 1970s, the Forest Service has adapted hand-held and fixed-mount infrared instruments (e.g., pyroelectric spot sensors, forward looking IR (FLIR) sensors) to fire suppression and management use. This infrared equipment, in addition to the line scanners, is available to the CDF through the Boise Interagency Fire Center in Boise, Idaho. Local vendors will supply hand-held infrared equipment on a buy or lease basis.

In the spring of 1983, a feasibility study was initiated to examine the application of advanced technology to forest fire detection and mapping. The study was conducted by NASA's Jet Propulsion Laboratory and sponsored by the Forest Service-USDA. The study defined an overall design approach to build a system which meets the Forest Service-USDA large-scale fire detection and mapping mission needs. The Forest Service-USDA intends to take advantage of the advanced technology system's design approach in the development of a new system designated "Firefly." Firefly will build upon research, development, and operational use conducted over the last 25 years, and engineering studies and analyses conducted over the last 5 years (Nichols, 1989). State-of-the-art (within cost constraints) data collection, processing, transmission, and display systems will be utilized by the Firefly system. The Firefly system is the basis for the mid-level system described in the concept system configuration of this report (Section 5).

Historically, the CDF has utilized infrared technology with the Forest Service line scanner systems, and either CDF- or independent contractor-owned FLIR systems. Many sources of infrared data were utilized with mixed results during the August/September 1987 California lightning fire outbreak (Weaver, 1988). A

major problem in mapping large fires with the Forest Service line scanner systems has been the system commitment to other areas just when they were required in California, resulting in the non-use of such systems due to the lack of availability. CDF cooperative work has led to the operational use of FLIR systems in both initial attack and fire mop-up activities.

The CDF is investigating remote sensing techniques and technologies that would allow near real-time gathering of fire information for fire managers and for air attack planning. The CDF is interested in: broad-scale information to provide an overview of the number, size, and relationships of fires over large geographic areas; strategic information useful at the region level; and information for management of individual fires. JPL has been directly involved in the use of remote sensing techniques to detect and monitor forest fires. JPL proposed to examine the application of advanced infrared technology to improve the gathering, integration, and synthesis of wildland fire data in the State of California. This report is the result of the Jet Propulsion Laboratory research on infrared technology for the CDF.

## 1.2 OBJECTIVE

The objectives of this report are to document the study of current and future user needs in infrared technology requirements for wildland fire management, to survey and identify infrared technologies that may be available to meet future needs, and to present a concept system configuration that could be useful in fire management and suppression in the State of California.

## 1.3 SCOPE

The scope of the document is limited to California Department of Forestry and Fire Protection user information needs in infrared technologies.

## 1.4 APPROACH

Identifying and defining bounds for the wildland fire detection and mapping problem unique to California were crucial to insure proper direction for this study. The fundamental approach used for this task is shown in Figure 1. Information regarding tactical and strategic fire suppression could best be obtained from the participants and line management directly involved. To support the study approach, discussions were held with CDF personnel. Officials at various levels in the CDF organization were interviewed during

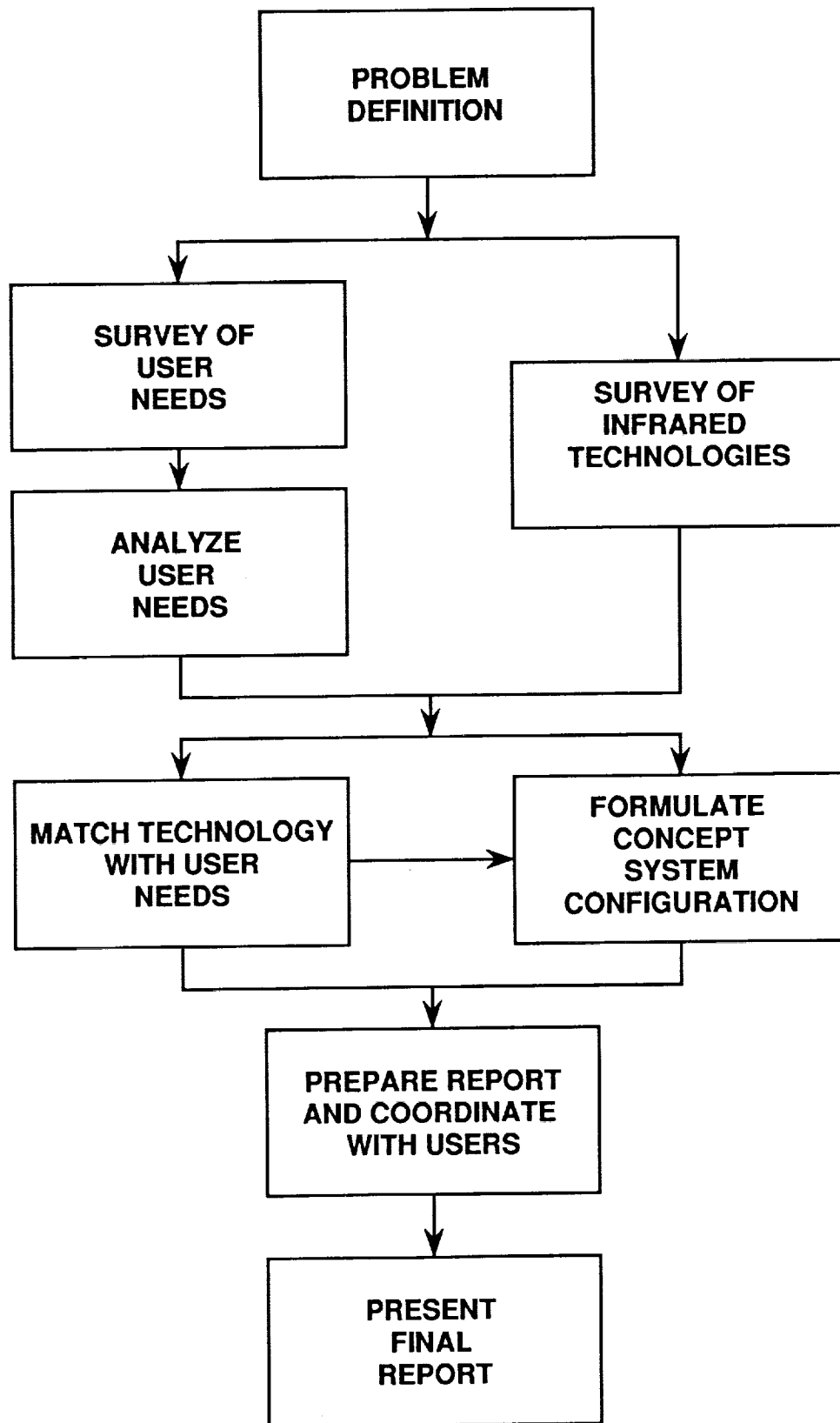


Figure 1. Approach of feasibility study.

August and September of 1989 to identify user information needs derived from airborne infrared monitoring equipment in wildland fire suppression and management in the State of California. The results of the CDF personnel survey are discussed in Section 2 of this report. A listing of individuals contacted is included in Appendix A. A summary of CDF personnel comments at the meetings is included in Appendix B.

The remainder of the task involved a study of emerging infrared technological developments as they relate to a concept system configuration, that will assist information gathering, reduction and processing needs for wildland fire management and suppression in the State of California. The applicable infrared technologies are discussed in Section 3 of this report.

Section 4 discusses the matching of technology and user needs to proceed with the development of a multi-level system to meet the defined needs.

The concept system configuration is presented in Section 5. The concept system configuration is a feasible approach to meeting the infrared needs of the user in a system that can be built. Trade-offs are shown to indicate how all or part of such a system could be developed. Section 5 ends with a discussion of the economic justification for a multi-level system.

Section 6 defines a conceptual design as the next step in the development of a system to support the CDF infrared technology needs into the next century.

The study supports the CDF infrared program objectives of:

1. Providing a statewide "big picture" intelligence base,
2. Providing a region coverage of wildland fire(s),
3. Providing single-fire intelligence such as hot spots or spot fires,
4. Providing statewide lightning detection for large numbers of starts or "busts,"
5. Providing information as close to initial attack as possible in a real-time format.





## SECTION 2

### SURVEY OF USER NEEDS

#### 2.1 CURRENT USER STATUS

Current infrared system user community status and technology insight needed to be determined prior to understanding user information needs. CDF personnel experience with IR equipment varies greatly. Several concerns were expressed by personnel responsible for implementation of infrared technologies at fires within CDF responsibilities. The user community areas of concern are availability of current IR equipment, type of data the equipment can produce, infrared equipment training, and the IR data quality.

CDF personnel regard the current non-availability of IR equipment within the incident management structure as a major concern. Some of the IR monitoring equipment, especially the Forest Service line scanners, are unavailable much of the time due to earlier commitments or higher priorities. When requests for IR monitoring support are submitted to BIFC, it is often not known until the equipment arrives just what type of IR equipment (line scanner and/or hand-held) will be sent. Additionally, it is not always known to what extent the equipment will be accompanied by experienced operating personnel and data interpreters. Getting any IR data within the first twelve hours of fire start is difficult due to equipment availability. Because of non-availability of equipment, IR data is currently not timely enough for application to initial attack or extended attack fire situations.

The data-producing capability of current IR systems is not well understood. The film product of the Forest Service line scanners is very different from the real-time video picture of a FLIR system or the audio indicator of a pyroelectric spot sensor. The user community does not completely realize what specific systems can and cannot do, and how they should be used is not well understood.

One difficulty with current IR systems is incomplete training of operators, interpreters and end users. Operators may know the operation of one system but not another due to unique and/or piecemeal assembly of IR systems in use in California. Except for a few individuals, training has not always kept pace with the hardware. For example, the Forest Service line scanners' normal operation requires specialized operators to produce a film product which

trained interpreters analyze prior to delivery to the end user (i.e., fire managers). The skill of the interpreters can be directly correlated to experience and current familiarity with the interpretative process. End users may be familiar with one system data product and not others that may be more applicable in a given incident. Obviously there can be more efficient operation if key personnel are brought up to date on the systems' capabilities and how to best utilize those systems.

A final concern has to do with the timeliness and accuracy of the data itself. IR data that is delivered to the user hours after the start of a fire is not as useful as near real-time data. When the Forest Service line scanner is available and utilized, the accuracy of the final output product is not always known or understood. Whenever delays in IR fire data collection occur, the usefulness of the data is limited to a historical perspective of the fire incident. Under some circumstances, there are also questions about the accuracy of line scanner data due to image distortion and difficulty in data correlation to a known geographical point. Currently, there is a need for skilled interpretation when working with infrared data.

## **2.2 BASIC FIRE INFORMATION NEEDS**

In understanding the information needs of the CDF user community, several significant points were noted. User requirements for information are stated in terms appropriate to fire management and suppression activities. These requirements include information about the following:

1. Fire location and intensity (capacity to view fire through smoke);
2. Current fire behavior, spot fires (hidden fires);
3. Predicted fire behavior;
4. Current fuel condition;
5. Effectiveness of aerial retardant drops;
6. Strategic planning.

The most important factor in the user requirements is that all information must be timely in that the earlier the information is received, the greater the possibility of formulating appropriate management decisions and the larger the number of management alternatives.

### 2.2.1 Fire Location and Intensity

In managing and suppressing a fire, fire management first needs timely information about the location and intensity of the fire. Specifically what is out there at the fire incident? Is a large fire burning or a small fire just getting started? Do hold-over fires remain? And where is the fire? Specific locations of the perimeters of both the main fire and hot spots outside the control lines associated with the fire perimeter are needed. An indication of the fire intensity at specific locations on the fire line is needed.

Fire location requires the incorporation of general geographic data correlated to the actual fire data.

### 2.2.2 Current Fire Behavior

A variety of information is needed to ascertain what a fire is doing. These types of information might include the following:

1. Rate of spread of the fire;
2. Fuel type being consumed;
3. Energy output of the fire (flame length of fire related to fuel type and fuel moisture);
4. Inhabited areas being threatened;
5. Factors influencing what the fire is doing (wind speed and direction, relative humidity, temperature, etc.).

### 2.2.3 Predicted Fire Behavior

To help estimate the fire's behavior, rate-of-spread models utilizing fuels, terrain, other data bases and dynamic weather information are available and can be incorporated into the infrared data analyses.

The prediction of fire behavior is dependent upon the weather, fuel types in the path of the fire, and terrain. Short-range weather forecasts and the long-range weather forecasts for the remainder of the fire campaign are critically important to suppression activities. The consideration for weather factors includes relative humidity, temperature, fuel moisture, and wind speed and direction. Weather factors influence not only fire behavior, but ambient air temperature that can greatly affect the performance and endurance of fire crews.

Another important parameter influencing a fire's behavior is terrain. Individual elements of terrain include elevation, slope aspect (direction in which a slope faces), and, of particular value to the fire strategist, slope gradient (steepness of slope).

The results of fire behavior models are of particular importance for fires at the urban/wildland intermix. Because such high value is placed on structures and associated human safety, there must be sufficient time to obtain and organize suppression resources to ensure adequate life and property protection. Robust fire models with accurate inputs can help secure critical time for suppression activities.

#### 2.2.4 Current Fuel Condition

Current fuel type and condition play a large role in determining the method by which the fire is attacked and the resources necessary for management and suppression.

Fuel models quantitatively describe the physical and chemical properties of fuel elements and fuel beds that govern flammability of various vegetation types. Properties include quantity, size, depth, heat content, and other factors. Fuel models describe vegetation in terms that permit useful fire-potential calculations for a variety of weather and topographic situations.

Generally, one channel in the near infrared and one channel in the middle infrared are required for most wildland vegetation applications. Optimal wavelength intervals for specific applications (disease, pest infestations, drought stress) would need to be determined. Current fuel conditions related to fuel moisture can be determined through the measuring of low leaf water content per leaf chlorophyll and high leaf temperatures using the selected infrared channels.

Infrared can be useful in monitoring and predicting current fuel conditions to verify and validate fuel models. Infrared can be useful in determining the fuel moisture of specific vegetation types and as such can produce data which can be incorporated into current fire behavior models that estimate fire spread rate and intensity. Infrared is useful in mapping major fuel type changes ( i.e., changes between grass and brush; timber and brush; conifer and hardwood; water and land; rocks and timber; rural and urban). Fire breaks outside the

perimeter of the fire would be discernible with infrared (e.g., roads, highways, streams, prepared fire breaks).

#### 2.2.5 Effectiveness of Aerial Retardant Drops

Aerial retardant drops can be monitored by infrared sensors mounted in an airborne platform. Infrared has the ability to penetrate smoke and darkness to obtain useful information on the location and adequacy of retardant drops. Monitoring retardant drops would need to be done by a system capable of obtaining information on a localized level to produce timely and useful information. The contrast between the cool retardant and the fire line as captured by the infrared system will provide ample timely information to determine the effectiveness of the aerial retardant drops.

#### 2.2.6 Strategic Planning

Strategic planning is needed both at the regional and the state levels. Synoptic information on single or multiple fires within a region would enable fire management personnel to determine what the fire is doing, where it is heading and how effective are the suppression activities. State-level information would provide an overview of the number, size, and relationships of fires over large geographical areas. Such strategic information would be important in understanding the severity of situations to better coordinate suppression plans and activities.

### 2.3 USER REQUIREMENTS AND INFRARED TECHNOLOGIES

Gathering fire information to meet many of the basic user requirements can be done through the use of IR remote sensing technology. IR data can be used to support both tactical and strategic fire suppression and management activities. The requirements are different for the fire operations and the planning functions.

Tactical fire monitoring activities supporting the Operations Section Chief emphasize speed and positioning accuracy. The Operations Section Chief needs to know where the fire is and where it is going as soon as possible after the fire start. Initial attack requires IR data in "real time," that is, within a few minutes of data acquisition. The data could be provided as a video image or as a quick-look snapshot. A variable field of view (zoom) is desirable to provide higher resolution of features within the scene. In order to discern if a particular fire containment line has been breached, the IR data must have a relative

positioning accuracy of a few meters. The IR data should be adequate to identify the fire perimeter and also to identify hot spots outside the main perimeter. Successive sets of data need to be sufficiently well correlated to give information about the fire's rate and direction of travel.

An important aspect of the tactical fire-monitoring activities is the rapid evaluation of the effectiveness of fire suppression activities, particularly the evaluation of air tanker drops. To this end, the air attack aircraft itself could serve as a good mounting platform for IR sensor equipment.

Strategic fire suppression and management planning requires a wide coverage of IR data to support the activities of the Plans Chief. With this strategic fire-mapping activity the emphasis is on breadth of coverage and convenience of reporting. A mid-level platform with a line scanner would provide information on the entire fire. This information would include the fire perimeter, hot spots outside the main perimeter, burnt-over areas, and indications of the fire intensity. A conveniently reproduced map product output is important so that data can be transmitted to fire camps, emergency control centers, region offices, and Sacramento if needed. Coverage needs to be available anywhere in California within six hours. Some of this large-scale information would need to be available within 30 minutes of collection, and repeat coverage needs to be available for each planning meeting. Within 6 to 12 hours strategic information needs to be available on the entire fire. The required positional accuracy on this strategic data is about 500 feet. FLIR systems could be used tactically to augment this strategic data on specific fire lines or sectors.

A synoptic view of the area of interest needs to be assembled within a week. Among other things, the large-scale IR data will provide briefing material, press release information, and documentation for post-fire lawsuits. Temporal IR data could provide, after extensive processing, an animation of the progress of the fire in a movie format to allow the study of the progression of the fire(s).

## **2.4 SUMMARY OF DISCUSSIONS WITH CDF PERSONNEL**

In recent years airborne infrared monitoring equipment has provided valuable support information to personnel fighting fires in California's wildlands. The ability of infrared to penetrate smoke cover affords a unique opportunity to monitor moving fire perimeters, to gauge fire intensity, to identify hot spots, and to evaluate the effectiveness of air tanker drops. To date, the potential contributions of infrared-monitoring techniques have not been fully realized

because of problems with equipment availability, cost, and personnel training. There have also been problems with providing infrared data in a timely manner and in a form that can be easily interpreted. These problems can and will be solved if the CDF places a high priority on gathering fire information through infrared data collection systems. The remainder of this report explores some of the technical possibilities for an IR program and indicates usage and management options.





## SECTION 3

### ADVANCED INFRARED TECHNOLOGY SURVEY

#### 3.1 INFRARED TECHNOLOGY

Man has been a remote sensing creature since his very beginnings. The ability of his eyes, ears, and nose to sense conditions in his surrounding environment often meant the difference between life and death. Remote sensing is simply the process of acquiring information from the environment by the use of a sensor that is not in physical contact with the object or phenomenon under study. Remote sensing can be done with sensors operating virtually anywhere in the electromagnetic spectrum, as well as with such non-electromagnetic types as acoustic and seismic. This report is limited to those fire management applications in which the remote sensing is done in the infrared portion of the electromagnetic spectrum. The infrared extends from the visible region at a wavelength of  $0.75\ \mu\text{m}$  to the microwave region at  $1000\ \mu\text{m}$ . Because of absorption by the earth's atmosphere, only a small portion of this range is usable for terrestrial applications. Infrared wavelengths are virtually unaffected by smoke, thus they are appropriate for fire suppression and management applications. Detailed discussions of infrared theory and technology are beyond the scope of this report but can be found in reference material (Colwell, 1983; Hudson, 1969; and Lloyd, 1975).

The thermal infrared bands commonly used in thermal IR systems suitable for wildland fire detection and mapping are  $3\text{-}5\ \mu\text{m}$  and  $8\text{-}12\ \mu\text{m}$ . These two bands are desired because the  $3\text{-}5\ \mu\text{m}$  band energy level peaks at the high temperatures associated with fires, and the  $8\text{-}12\ \mu\text{m}$  band energy level peaks at ambient earth temperatures allowing for detection of earth surface features. Instruments that use the  $3\text{-}5\ \mu\text{m}$  band detect active fires very well but do not detect cool features such as vegetation or topographic features. The  $3\text{-}5\ \mu\text{m}$  band instruments are also sensitive to reflected energy sources such as sunlight off rock outcroppings, water and ice. The  $8\text{-}12\ \mu\text{m}$  band instruments detect vegetation and topography with good detail but can be disrupted by high energy sources such as fire or solar glint.

Infrared systems can be grouped as either imaging or non-imaging. IR sensors rely upon the natural emission of radiant energy which occurs in all objects and

is directly related to the temperature of the object. Active sensors carry their own radiation source along with their receiver.

Imaging systems provide an image of the scene in the field of view and the temperature of objects or areas within the scene is deduced, usually in a relative manner, by "brightness" of those objects or areas compared to the background. An imaging system thus displays the total scene and hot objects can be located based on their relationship to the total scene. Imaging IR systems provide an image of the covered area which is viewed at the sensor's display, an accompanying video monitor, a hard copy printout, or some combination of the above. Video-compatible systems can also record the IR images for subsequent playback on standard video tape recorders, and may include audio annotation. Non-imaging systems provide a single number output indication of the temperature of an object or area in either a qualitative (light, horn, etc.), quantitative (calibrated temperature reading), or relative (deflection of meter from an uncalibrated reference) manner.

There are many types of infrared instruments which can assist the CDF in its fire mapping, detection, suppression and monitoring roles. This section of the report discusses the full range of available sensors. Applications of these sensors may be mentioned, but are not extensive. The survey considers commercially available, non-military instruments sensitive in the IR wavelengths.

For this survey the available sensors will be divided into four major categories: FLIRs, Solid State area imagers, IR line scanners, and spot sensors. The first three types are imaging sensors, which provide a two-dimensional spatial image of whatever they observe. This image is usually (but not always) displayed in a video-compatible format. Spot sensors (also known as non-imaging sensors) provide a single output based on the average of what is in the sensor field of view. The output of these sensors is some signal (acoustic, optical or electrical) which is a function of the total intensity of the image within the sensor field of view (FOV).

### 3.2 FORWARD LOOKING INFRARED SENSORS

Forward looking IR (FLIR) sensors are the most widely distributed IR sensors, since they were developed primarily for the military. Modern FLIR sensors are used for everything from search-and-rescue to missile guidance. The primary reason the military has put so much effort into the development of FLIR is their

capability to image terrestrial scenes through smoke and haze with or without solar illumination. The wave band chosen (3-5  $\mu\text{m}$ , 8-14  $\mu\text{m}$ , or a combination of those bands) is optimized for detection of small temperature differences around nominal ambient temperatures. The typical FLIR system operating characteristics are shown in Table 1.

Tactically there are many fire-related applications where FLIR use is superior to other IR methods. FLIRs used on small fires or spot fires associated with large fires can give a close-up IR "look" at the size and relative location to the surrounding physical features. FLIRs are ideal for small area surveillance and monitoring as they can indicate fire change and status as time progresses. FLIR units can be hand-held or fixed-mounted onto either helicopters or fixed-wing aircraft. Aerial portability allows rapid transport to the site of any suspected or actual fire occurrence. FLIR systems require cryogenic cooling by liquid nitrogen (LN2) or other means. FLIRs work well as fire mop-up tools that can view the area after the burn is completed to assure that all hot spots are known and adequately treated prior to crew release.

FLIRs, used in conjunction with aerial line scanner systems on active large fires, can gather IR data on crucial portions of the fire perimeter. They can indicate whether the fire is contained within a firebreak or has crossed over. Tactically FLIRs can be used to update data along selected portions of the perimeter as required.

Many FLIRs have zoom lens capabilities to provide higher resolution over a smaller angle. There are two types of FLIRs available on the market: parallel and serial scan FLIRs. Figures 2 and 3 show how these FLIRs construct images.

TABLE 1: FLIR CHARACTERISTICS

Spectral Band:	3-5 $\mu\text{m}$ and/or 8-12 $\mu\text{m}$
Field of View:	30° (vertical) x 40° (horizontal)
Image spatial resolution (detector instantaneous field of view -- IFOV):	0.057° (square)
Thermal resolution within the image (Noise Equivalent Temp):	0.2 °C

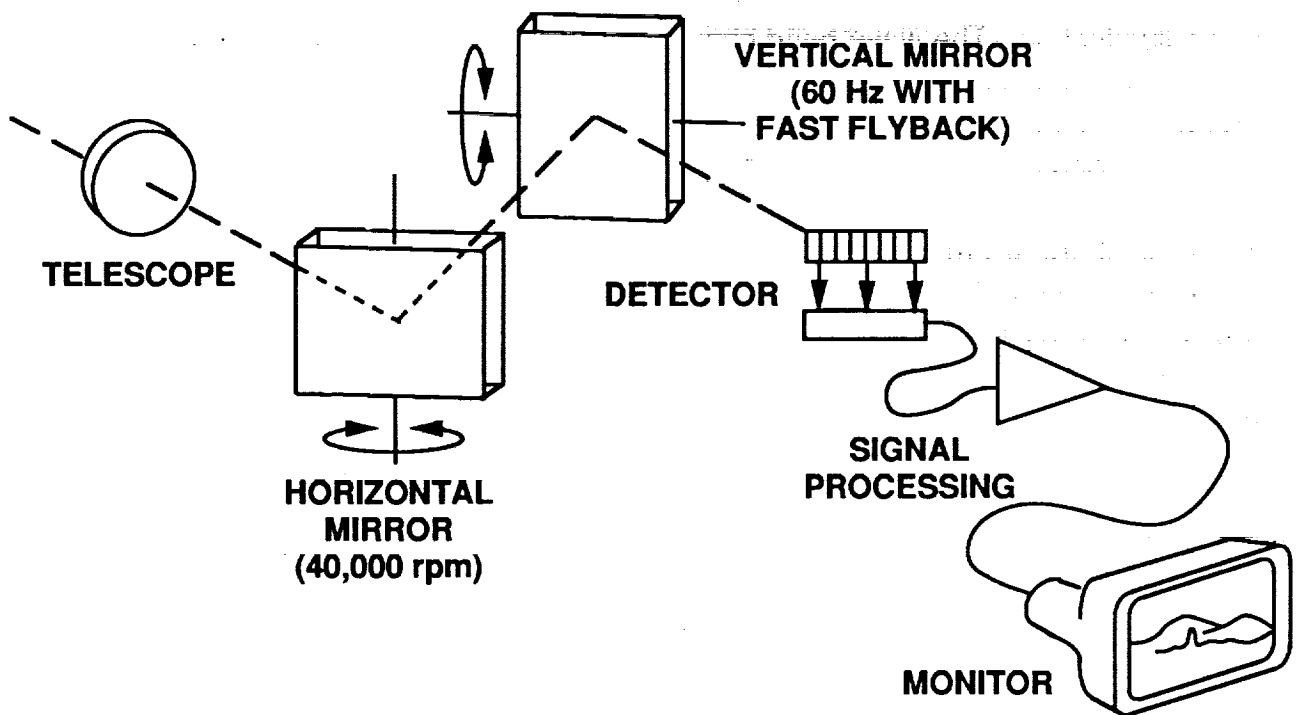


Figure 2. Serial scan FLIR.

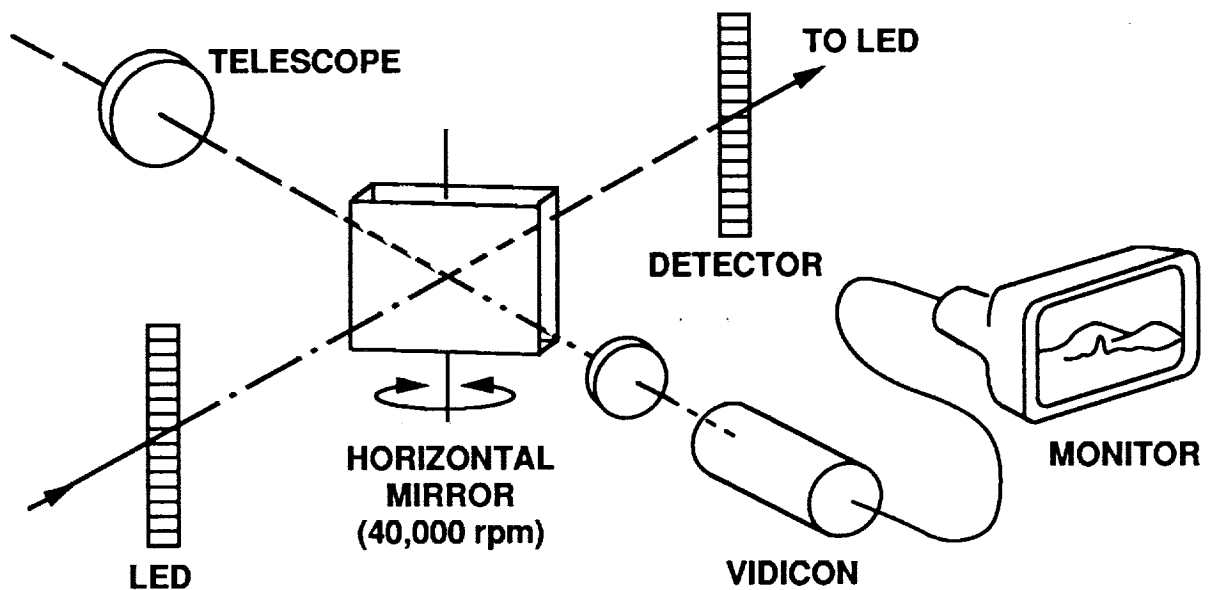


Figure 3. Parallel scan FLIR.

### 3.2.1 Serial Scan FLIRs

Serial scan FLIRs are the most widely manufactured FLIRs, because the technologies for mechanical scanning are much more mature than those for detector fabrication. As Figure 2 shows, serial scan FLIRs rely on a few detectors and two mirrors, one of which is operating at an extremely high speed (40,000 rpm is not uncommon). Using the same detector to sense the whole scene causes the system to be less sensitive, because the detector spends less time at each spot within the FOV. However, serial scan FLIRs generate extremely uniform images because a single detector is used to view the whole image. Images from serial scan FLIRs have very few streaks and shaded spots.

Some notable manufacturers of serial scan FLIRs are listed in Table 2, with comments. Although several FLIR units are commercially available, most manufacturers have developed their product line with the military market in mind. The military places an emphasis on formal quality assurance, including environmental testing, parts control, and military quality documentation. The marketing infra-structure tends to add to the price of each FLIR, with little return

TABLE 2: SERIAL SCAN FLIR MANUFACTURERS

<u>MANUFACTURER</u>	<u>COMMENTS</u>
Barr and Stroud, Ltd.	Marketed in USA by Magnavox. Expensive(>\$100,000), but very sensitive.
FLIR Systems International (FSI)	Good reputation for small, inexpensive (<\$50,000), but useful FLIRs.
Honeywell Electro-Optical Division	Full range of serial scan FLIRs. Expensive(>\$100,000), but very sensitive.
Inframetrics	Good reputation for small, inexpensive (<\$50,000), but useful FLIRs.
Kollmorgan	Extremely compact FLIR, good sensitivity, expensive (>\$100,000).
Marconi	The British "Common Module FLIR" expensive (>\$100,000), but very sensitive.

for the non-military customer. Manufacturers such as Inframetrics and FLIR Systems, on the other hand, have targeted commercial sector applications, in addition to some military work. The resulting product tends to be less expensive, slightly less sensitive, and not as sophisticated. The commercial design choice is an advantage for the CDF, as the system is designed to be easy to use, rugged, and portable.

### 3.2.2 Parallel Scan FLIRs

In the 1970s, the military funded efforts to improve sensitivity and reliability of FLIRs by replacing one dimension of mirror movement with a long detector array, as shown in Figure 3. The critical technology moved from the high-speed mirror to the detector array and its processing electronics. At the time, a great deal of effort was put into making the FLIR smaller and lighter.

Most military FLIRs in critical applications are parallel scan FLIRs. However, parallel scan FLIRs are no more reliable than serial scan FLIRs, and are usually considerably heavier and bulkier. The increased reliability didn't occur because as the detector array became larger, the heat generated at the focal plane grew, causing more severe requirements on the cooler, which became the weak link in the chain. Cooler technology has been improving, allowing high reliability parallel scan FLIRs to be developed in the near future.

Parallel scan FLIRs (in general) are more sensitive, and have higher resolution, due to the longer amount of time each detector can view a given spot in the scene. However, parallel scan FLIRs produce images which have considerable non-uniformity and streaking, when compared to a serial scan FLIR. Some notable manufacturers of parallel scan FLIRs are listed in Table 3, with comments.

All of the parallel scan FLIR manufacturers have developed their product with the military in mind. Parallel scan FLIR systems are expensive, approximately 1.5 to 2 times as expensive as a similar serial scan FLIR. The exception to this rule is the Hughes Probeye, which is a small, relatively inexpensive, hand-held FLIR. The Probeye is sensitive to 2 to 4  $\mu\text{m}$  wavelengths, and uses a lead salt detector (PbS) rather than mercury cadmium telluride (HgCdTe). The Probeye is quite a bit less sensitive (10 to 100 times less) than other parallel scan FLIRs, but is useful for hand-held, short-range applications.

TABLE 3: PARALLEL SCAN FLIR MANUFACTURERS

<u>MANUFACTURER</u>	<u>COMMENTS</u>
Honeywell	Manufactures U.S. Army "Common Module." Expensive (>\$100,000).
Hughes	Manufactures many types, including Probeye, a hand-held unit. Varies in price (\$15,000 to \$30,000).
Northrop	Manufactures U.S. Army "Common Module." Expensive (>\$100,000).
Texas Instruments	Manufactures U.S. Navy "Common Module." Expensive (>\$100,000).

### 3.3 SOLID STATE DEVICES

Solid state devices for IR imaging include those devices which form an image without any moving mirrors. Being able to image with no moving parts allows the fabrication of very small, rugged imagers. Examples of solid state devices are more common in the visible wavelengths, where detector materials are more mature. Some examples are vidicon image tubes and charge coupled device (CCD) imagers; both of these are found in standard video cameras or closed circuit TV systems. However, some of these devices are tailored towards operation in low-light situations, either with IR or intensified visible detectors. These devices include pyroelectric imagers, image intensifiers, and IR area array imagers.

#### 3.3.1 Pyroelectric Imagers

Pyroelectric imagers are sensitive from about 0.1 to 100 microns. These devices sense light (within the wavelengths mentioned) by heating up slightly as photons are absorbed into the detector material. Readout electronics measure the electrical characteristics of the material, which change as a function of temperature. Pyroelectric materials, including lithium tantalate ( $\text{LiTaO}_3$ ) and lithium niobate ( $\text{LiNO}_3$ ) have been used on infrared vidicons for many years. In general, pyroelectric devices are 10 to 100 times less sensitive than FLIRs. These sensors are similar to standard vidicons, except the sensing

material on the front is changed. Pyroelectric imagers are relatively inexpensive, but are quite fragile (just as visible vidicons are).

Recent work in pyroelectric detector technology has led to the development of area arrays of pyroelectric detectors. Arrays as large as 250 x 250 elements have been fabricated. These devices are very rugged and portable, because the primary application they are aimed at is IR rifle sights.

### 3.3.2 Image Intensifiers

Image-intensified CCD detectors are visible detectors mated with a microchannel plate intensifier, similar to the military night vision goggle. While these devices are handy for navigation or surveillance at extremely low light levels, they are not particularly useful for fire fighting, for two reasons. First, they respond in wavelengths which have very poor smoke transmission. Second, image-intensified CCD's tend to "bloom," or saturate when bright objects such as fire are present in the FOV.

### 3.3.3 IR Area Arrays

For many years, the technology development of two-dimensional arrays of IR detectors has promised extremely small, rugged, yet highly sensitive IR imaging systems. Detector materials have not matured to the point where this is completely so. The three most promising materials are platinum silicide (PtSi), indium antimonide (InSb), and mercury cadmium telluride (HgCdTe). Table 4 summarizes the characteristics of each material. Presently, PtSi is available in 512 x 512 element arrays, which is certainly a high enough resolution for imaging. The efficiency of the PtSi material is 10 to 30 times less sensitive than HgCdTe or InSb, but has such good uniformity that imagers utilizing it are quite useful. InSb and HgCdTe arrays are available in 128 x 128 arrays, which provide a somewhat coarse resolution image. These arrays are extremely sensitive, though, and as technology (and material maturity) improves, larger format arrays will become available. All three of these materials require cryogenic cooling for operation. Cryogenic cooling is required because they detect photons by sensing an exchange of energy from photons to electrons. Cooling allows detection of electrons which have absorbed only a small amount of energy, commensurate with the energy in an IR photon.

IR area arrays are still a developmental technology, but are finding limited use on satellite platforms as the detector technology advances.



TABLE 4: IR AREA ARRAY MATERIALS

<u>MATERIAL</u>	<u>MAX. ARRAY SIZE</u>	<u>COOLING</u>	<u>SENSITIVITY</u>
Platinum Silicide	512 x 512	77°K	Moderate
Indium Antimonide	128 x 128	77°K	Extremely high
Mercury Cadmium Telluride	128 x 128	60°K to 140°K	Extremely high

### 3.4 INFRARED LINE SCANNERS

IR line scanners have a long history of use in fire fighting and monitoring situations. The USDA Forest Service has experimented with IR line scanners since 1962. The first line scanners utilized were off-the-shelf military line scanners which were subsequently modified to attain effective fire detection. Two fundamentally different types of line scanners, "pushbroom" and "whiskbroom," have been developed. The two line scanner types are compared in Figure 4. The "whiskbroom" line scanner relies on a high-speed spinning mirror and few detectors to image the field of view, and aircraft velocity to join consecutive fields of view to form the strip image. The "pushbroom" line scanner has no moving parts, just a very wide detector array. Aircraft velocity joins consecutive fields of view as with whiskbroom imagers. To date, only whiskbroom line scanners have been implemented in any real sense for fire applications. However, as detector technology improves, and detector arrays become larger, pushbroom line scanners could be used for fire suppression and management.

#### 3.4.1 Whiskbroom Line Scanners

The whiskbroom line scanners use a single or dual element detector. The field of view is rapidly swept across the flight line in a direction perpendicular to the aircraft's axis (which is not necessarily the direction of aircraft motion). The scanning mirror must move fast and must be rigidly supported to produce good images. Whiskbroom line scanners have been deployed by the military for IR reconnaissance since the Korean War. Whiskbroom line scanners are commercially available from a number of sources, as shown in Table 5.

TABLE 5: WHISKBROOM LINE SCANNER SOURCES

<u>MANUFACTURER</u>	<u>COMMENTS</u>
Barr and Stroud	Very compact unit. Narrow field of view. No mods from production unit supported. Limited production. Inexpensive (<\$200,000).
British Aerospace	Compact unit. Narrow field of view. No mods from production supported. Inexpensive (<\$200,000).
Daedalus Enterprises	Large unit. Wide field of view available (80°+). Custom work available. Many different multispectral models available. Expensive (>\$350,000).
LORAL (Honeywell EOD)	Moderate size unit. Custom work available. Expensive (>\$500,000).
Kollmorgan Corp.	Very compact unit. Expensive (>\$500,000).
Magnavox	Compact unit (modified Barr and Stroud FLIR). Custom work only. Very expensive (>\$700,000).
Texas Instruments	Moderate size unit. No custom work supported. Expensive (>\$500,000).

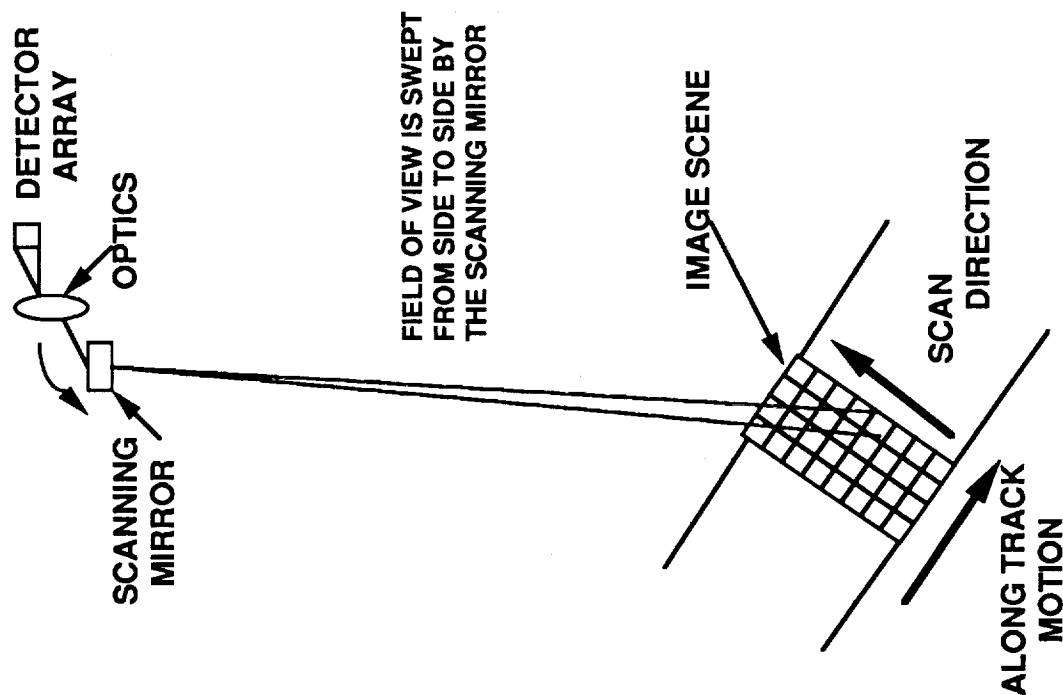
#### 3.4.2 Pushbroom Line Scanners

The pushbroom line scanner is not in production anywhere. However, this is a possible sensor to be used in a satellite application, because of its inherent high reliability (no moving parts, and cooling in space can be passive). These sensors would be VERY expensive (about 20 times more expensive than the most expensive imager mentioned so far), but are valuable for providing a large regional view. Most satellite orbits allow for one or two passes per day, at the most, so this is not a good method of collecting tactical data.

### 3.5 SPOT SENSORS

Spot sensors are non-imaging IR sensors which respond in some manner to the heat source or temperature change present in the field of view. These sensors typically have only one detector element, so there is no resolution within the optical FOV. The output of the instrument can be a meter, an audible signal, a

## WHISKBROOM LINE SCANNER



## PUSHBROOM LINE SCANNER

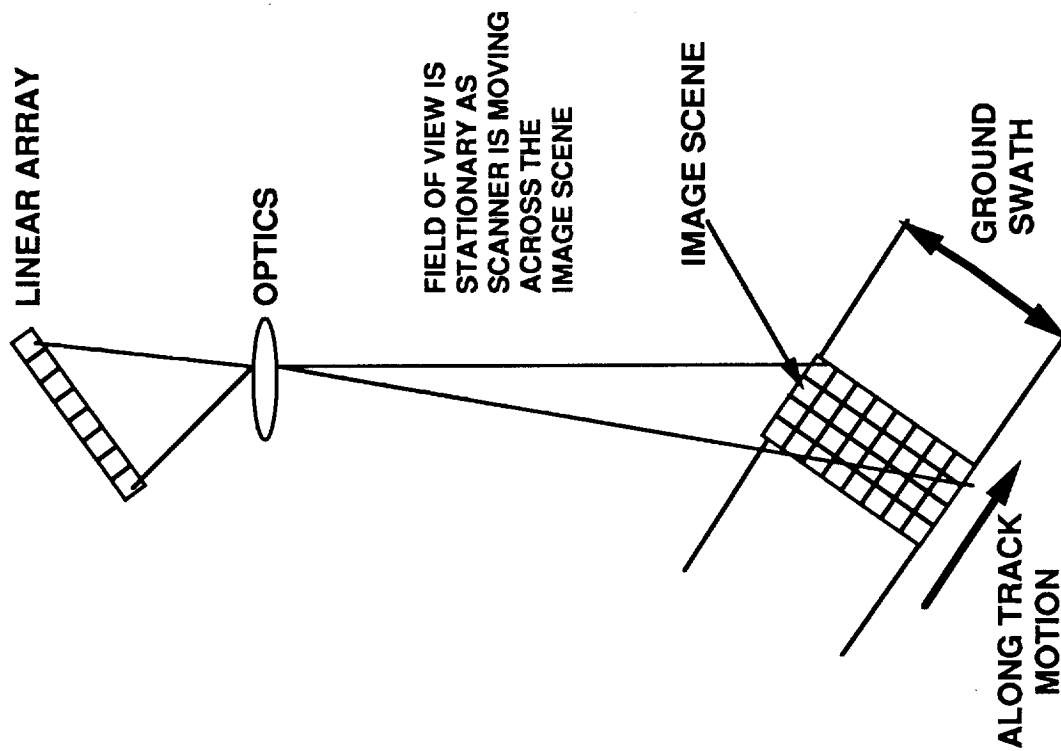


Figure 4. Line scanner comparison.

flashing or steady light, or some combination of the above. One implementation of this concept that is very useful to fire fighters is the pyroelectric "flashlight." Such a device (e.g., as manufactured by Pyr-Olex) emits a tone whose frequency is dependent on the intensity of objects within the FOV. Pointing this sensor at a cool rock will cause the device to emit no sound, while pointing it at a small fire will cause it to emit a 500 Hz tone. Pointing it at a larger or more intense fire will raise the frequency of the tone. This device is inexpensive, extremely rugged, and might be of use in extremely dense smoke or in mop-up, where the fire is not visible. Obviously, an operator of such an instrument would need training and practice to determine heat sources of different sizes and temperatures.

### 3.6 FIXED POSITION SENSORS

Located on high points (mountain tops, fire lookouts) fixed position sensor stations observe the horizon through 360° scanners. The principle behind fixed position sensor systems is to obtain maximum contrast between the background of the signal narrow field optical system and the apparent fire being observed by the sensor as it scans the whole of the observable landscape. Natural obstacles, towers, "authorized" smoke (e.g., lumber mills, refuse dumps, etc.) are mapped prior to detection operations to avoid false alarms.

Fixed position sensor systems are limited by line of sight of the instrument; thus, numerous stations would be required to completely map a region of interest. The numerous systems would require a specialized data transmission network to cover all the sensor stations for a region. A data-processing system would be required to process the data from the various stations. The data would need to be collected, cross-checked, and correlated to a geographical base to establish detection of actual fires versus false alarms.

The availability of such systems is extremely limited to a few manufacturers worldwide. One such manufacturer is the French company Blomme Automation. Blomme Automation has a dual system consisting of a station for smoke identification and a station for fire detection. The stations can be operated either together or independently. The horizon is divided into sectors in which an infrared laser pulse is emitted. The impact of the IR ray on smoke causes back-scattering of a small part of the incident energy to the system. The time measured between the moment at which the laser pulse is emitted and that at which its echo is detected determines the distance between the smoke and the detection station to record the actual position of the fire. The IR fire detector

sensor system will discover the fire, due to the contrast with the background and with the known radiating profile of the landscape, and indicate the direction (elevation and azimuth) from which it is observed. The system requires a central processing facility to collect the data from the different stations, make the cross-check calculations of the detections of the fire(s) detected with the topographical data, control the alarm, archive the fires, and plot on a map the profile and direction of the signal detected. The company claims a single station can cover up to a 100-square-mile area, viewing up to 12 miles distant with a resolution of 150 feet. The operation temperature range is  $-10^{\circ}\text{C}$  to  $+60^{\circ}\text{C}$ . The system lacks the capability to penetrate high moisture content phenomenon such as clouds or photo-chemical smog.



## SECTION 4

### MATCHING TECHNOLOGY AND USER NEEDS

The technology survey covered a wide variety of existing fundamental and advanced infrared technologies as well as several promising emerging technologies that may be suited to aid the information gathering necessary to meet CDF fire management needs. Such infrared technology can fulfill many of the information requirements of the CDF for fire management. Basic user needs and requirements for information include the need to know the location and intensity of fires and the current and forecasted behavior of fires. These needs can be met with the measurement and modeling of the local and regional environment and the functional use of the technology.

The design of a system should be approached from the fundamental requirement of a "user friendly" system with reliability and maintainability considerations foremost. The advanced technology must translate into cost savings and improved performance if the system is to meet the information need in fire management of the CDF. A major concern regarding the practical application of advancing technology to fire mapping and detection is the apparent complexity of the system that could result. Such complexity is clearly not workable in a tactical situation where major decisions would be based on a system that may or may not be up and working.

Complex technology could affect the performance of the entire fire management system in that a high degree of training may be necessary in order to operate the system and to maintain the system. The reliability of the system may be reduced if this training is neglected.

Matching technology to user requirements was completed by comparing the capability of each technology to each user need. The concept system configuration in the following section serves as a primary result of matching technology to requirements.





## SECTION 5

### CONCEPT SYSTEM CONFIGURATION

The concept system configuration as shown in Figure 5 was prepared with regard to future information needs and what emerging and available infrared technologies might be present in the 1990s. The concept system configuration addresses the multi-level information collection needs of the CDF while also requiring an effort to be modular in concept. Modularity will allow options as pertaining to need and resources available for implementing part or all of a potential system. The concept system configuration is intended as a device upon which a subsequent conceptual design may be based. The basic components of such a system are summarized in the Technology Evaluation Matrix (Figure 6) and discussed in the following section. The detailed components and their design would be determined in a project conceptual design phase as a follow-on to this study.

#### 5.1 SENSOR PLATFORMS

##### 5.1.1 Low-Level Platform

The obvious low-level platform would be the CDF aircraft (the Cessna 337 air attack aircraft) currently utilized by the initial air attack officer. The initial air attack planes are the first aircraft at the fire incident and are stationed over the fire in the critical times when fire management decisions need to be made. Upon arrival at a fire incident by the air attack aircraft, IR data could be gathered and transmission to fire suppression personnel could begin. Tactical information could be gathered from the air attack aircraft throughout the duration of the fire incident. IR mounted in the air attack aircraft would enhance the capability of the air attack officer to observe the wildland fire and also, with the appropriate down link, allow the Incident Commander a better tactical view of the scene. The air attack aircraft would be required to operate with the airborne mapping equipment and the operator at altitudes ranging between 1,000 and 10,000 feet above the ground level for extended periods of time. The infrared equipment on the low-level platform could be hand-held or fix-mounted (rigid or gimbaled).

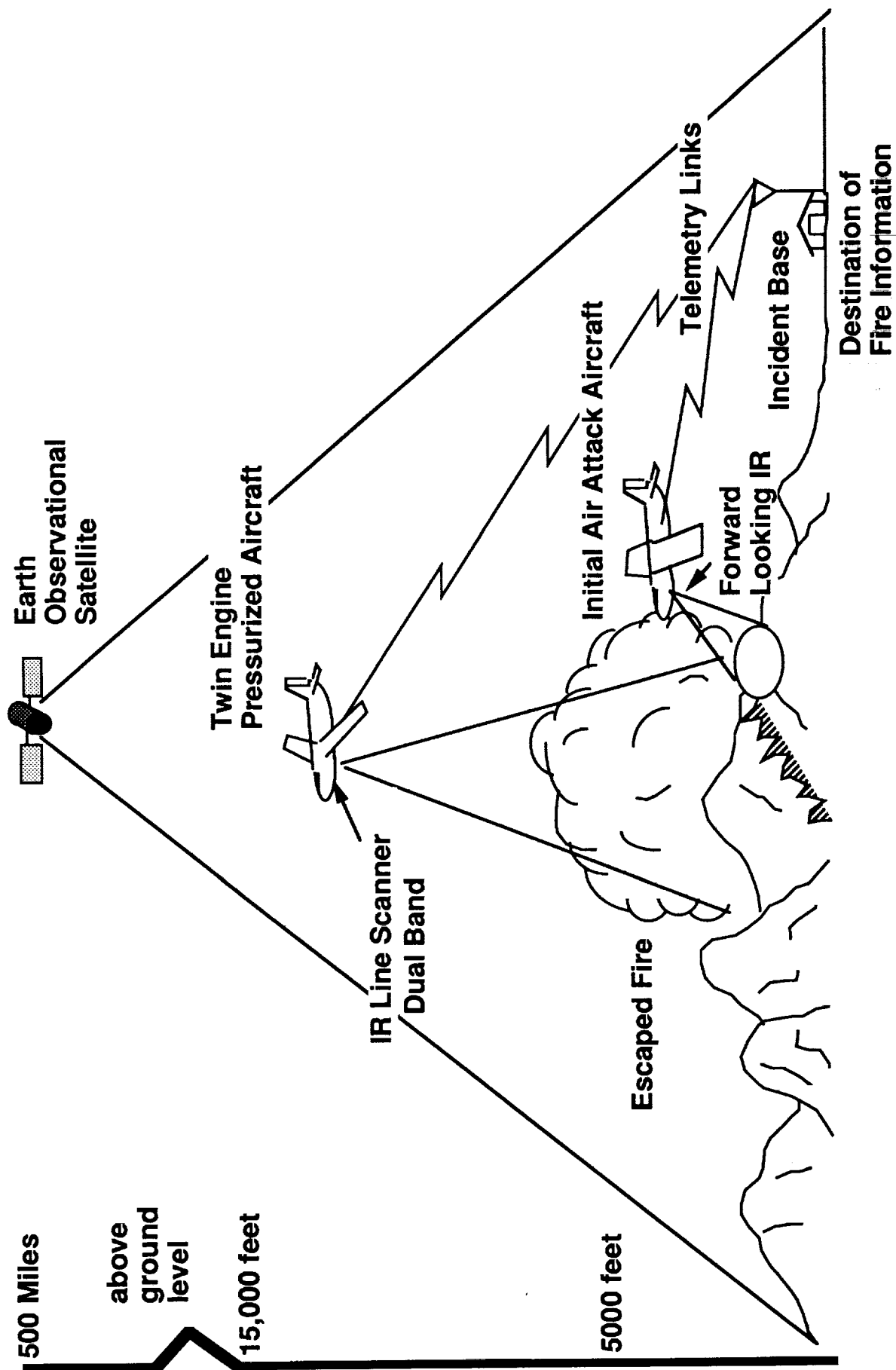


Figure 5. Concept system configuration.

<b>TECHNOLOGY CRITERIA</b>	<b>LOW LEVEL</b>	<b>MID LEVEL</b>	<b>HIGH LEVEL</b>	<b>HAND-HELD SPOT</b>	<b>FIXED POSITION</b>
<b>COST</b>	\$30,000 to \$150,000	\$350,000 to \$1,000,000	Systems in millions, data in thousands depending upon coverage area	\$500 to \$4000	\$200,000 to \$250,000 per station
<b>AVAILABILITY</b>	Off-shelf	8-10 months /order	Federal agencies	Off-shelf	8-10 months /order
<b>COVERAGE</b>	100 to 200 acres	300 to 500 square miles per hour	100 x100 nautical miles per image	2-3 foot diameter at 20 feet from target	Limited by line of sight - estimated to be 35,000 acres per station
<b>TIMELINESS</b>	Real-time once at scene	Within 20 minutes once at scene	Depends on cloud cover, then within two weeks	Real-time once at scene	Within 10 minutes
<b>OUTPUT PRODUCT</b>	Real-time image non-georeferenced	Geo-referenced map plotted at any map scale	Film, photograph or computer- compatible tape	Audible alarm	Location plot on map
<b>RELIABILITY</b>	High - proven through years of use	High - proven through years of use	Products are of high quality	High - simple, rugged design	Unknown
<b>MAINTAINABILITY</b>	Requires periodic maintenance	Requires periodic maintenance	Not applicable, handled by federal agency	Easily maintained	Requires periodic maintenance
<b>OPERATIONS</b>	Operator, aircraft, local maps, radios needed	Operator, aircraft, radio, InciNet ground system	MOU with agency, image processor and display facility	Operator	Data transmission, processing, and display facilities
<b>TRAINING</b>	Specialized initial and recurrent	On-line standard tutorial available	Specialized initial and recurrent	Easy to use with manual	Specialized initial and recurrent

Figure 6. Technology Evaluation Matrix: concept system configuration major components.

### 5.1.2 Mid-Level Platform

The likely candidate for a sensing platform at the mid-level would be a pressurized turboprop aircraft (e.g., Beechcraft King Air, Beechcraft Duke). The mid-level platform would provide the large area or regional coverage necessary to get a synoptic view of a large single fire, or a complex of fires. A turboprop aircraft would be fast and versatile, providing a broad range of regions to be covered in a short time period. The mid-level platform, with a large load capacity, would be capable of flying the appropriate infrared mapping equipment ( $\leq 400$  pounds), and operational personnel including a pilot and system operator as a minimum. The aircraft would be required to fly at altitudes ranging between 1,000 and 25,000 feet above ground level.

The aircraft navigation system measures the aircraft position, attitude and heading for real-time determination of vectors to objects in the infrared imagery. The aircraft navigation system would utilize the Global Positioning System (GPS) to provide a determination of aircraft position. Directional gyroscopes and a north-seeking compass would be utilized for aircraft heading and attitude determination.

### 5.1.3 High-Level Platform

The high-level (60,000 feet above ground level) large area coverage could be achieved either via earth observing satellite (NASA's Landsat or NOAA's polar-orbiting weather satellites as described by Matson, et al. [1984]) or via a very high-flying aircraft (such as NASA's ER-2, a high-altitude reconnaissance aircraft). Either of these platforms could provide the "big picture" view of a large region or the total statewide view. The large view would be useful in strategic planning briefings, public relations briefings, or with press releases. Operationally, the large view IR data would be limited by lack of timely data access, availability of platform when optimal, accessibility, and the inherent coarse spatial resolution.

Earth observing satellites are stationed at altitudes much higher than aircraft, allowing rapid large area coverage with less extreme viewing angles. The earth observing satellite orbit is fixed in time, direction and pointing orientation. The satellite orbit does not allow the system to be available on call, as with an aircraft, but at the fixed time and track determined for that type of system. The satellite's predefined orbit often precludes coverage of a given target for any given time. Such coverage could be achieved with a geosynchronous orbiting

satellite, but spatial resolution would be limited due to the extreme altitudes required for geosynchronous operation (22,000 miles). In addition to the satellite orbit limitations, and the low spatial resolution of satellite systems, there is the problem that the area of interest may be obscured by clouds in which case the satellite platform would not provide a viable option.

NASA has flown the ER-2 reconnaissance aircraft at altitudes above 60,000 feet to perform IR observations for a variety of applications. From that altitude and with the high speed of the aircraft, very large areas can be covered in a short period of time. The high altitude performance allows for the image product to be scaled very closely to a U.S. Geological Survey 15-minute quad map. The geo-referencing of the image to match a map base is simplified due to the lack of image distortion from above 60,000 feet. However, the ER-2 aircraft are few in number and not necessarily available when needed to fly an operational task such as fire management. The ER-2 is limited to high altitudes and thus cannot fly at various altitudes to optimize the imagery quality or fly under clouds when necessary to obtain imagery. A cooperative agreement would be necessary between CDF and NASA/AMES to establish an acceptable availability support program on a routine basis for use of the ER-2 in fire suppression observations.

## 5.2 SENSORS

The concept system configuration sensors are summarized in the Technology Evaluation Matrix (Figure 7) and discussed in the following sections.

### 5.2.1 Low-Level Sensor

The low-level sensor system would need to be compatible with the platform available for this task. The size of the platform dictates that the sensor be compact, lightweight, and easy to mount or hold during operation. FLIRs are the obvious choice for this component of the system. FLIRs are characterized as being operable either hand-held or mounted onto the platform. FLIRs are relatively lightweight and transportable, but they require cryogenic cooling usually with liquid nitrogen. FLIRs operate in either the 3-5 or 8-12  $\mu\text{m}$  bands, or in a combination of the two. As discussed in Section 3.2, several models are commercially available, and are standard (NTSC) video compatible. CDF has fire management experience in the use of FLIRs (Weaver, 1983).

TECHNOLOGY CRITERIA	LOW LEVEL		MID LEVEL	HIGH LEVEL	HAND-HELD SPOT	FIXED POSITION
	TYPE	FLIRS	LINE SCANNER	LINE SCANNER- LINEAR ARRAY	NON-IMAGERS	360° SCANNERS
COST		\$30,000 to \$150,000	\$350,000 to \$1,000,000	Systems in millions, data in thousands depending upon coverage area	\$500 to \$4000	\$160,000 to \$200,000
RESOLUTION		Spatial: 1 mrad Thermal: 0.1 ° F	Spatial: 1 to 2mrad Thermal: ≥600°C of 0.5 square feet	Spatial: 1 to 2mrad Thermal: 400- 500°C of 2 hectares	Responds to >200° F one square foot at 20 feet	Spatial: locates 3x6-foot fire at 12 miles Thermal: ≥600°C
AVAILABILITY		Off-shelf	8-10 months /order	Through agencies	Off-shelf	8-10 months /order
COOLING REQUIREMENTS		Liquid nitrogen or argon	Liquid nitrogen	Not applicable	None	Mechanical
PHYSICAL SIZE AND WEIGHT		Some hand-held, others mounted 30-80 pounds	Approximately 25x20x20 inches 100-120 pounds	Not applicable	Approximately 8x3 inches 2-3 pounds	Approximately 4x2x2 feet 150-200 pounds
POWER		22 to 32 volts DC at 15 amp minimum	28 to 32 volts DC at 40 amps	Not applicable	2-4 standard 9-volt batteries	1 kilowatt from local supply or solar battery
RELIABILITY, MAINTAINABILITY		High - proven through years of use	High - proven through years of use	Not applicable	High -simple design	Unknown

Figure 7. Technology Evaluation Matrix: Infrared sensors.

### 5.2.2 Mid-Level Sensor

The mid-level sensor would be modelled on the Firefly sensor system currently under development at JPL (Nichols, 1989). The sensor receives infrared radiation from the fire and converts this radiation into electrical signals for subsequent processing. The sensor consists of a special purpose IR line scanner to detect and locate fire and flame hot spots on the ground. Infrared scene emittance is gathered in two IR spectral regions to provide false alarm rejection with optimum sensitivity detection. The requirements for bi-spectral imaging, large FOV, and high spatial resolution make an IR line scanner the sensor of choice. The Firefly sensor requirements as listed in Table 6 could serve as the potential IR sensor requirements for a mid-level sensor system.

Functionally, the mid-level IR sensor must address the two primary tasks of mapping (perimeters of) established fires and detection of point fires ("hot spots") for initial fire detection and mop-up operations. Both tasks imply requirements which must be met by the sensor. Mapping large fires requires large field of view (at least 80 degrees cross track) and high sensitivity in the long-wave IR channel for terrain imaging. Hot spot detection requires bi-spectral imaging for false alarm rejection, wide FOV to maximize the area searched, and high sensitivity in both spectral channels.

The secondary task of the mid-level system would be to provide synoptic data for a region or a complex of fires. This data would be collected temporally allowing conditions to be monitored from time period to time period. Synoptic coverage will provide data for strategic planning by fire suppression personnel.

Due to the very small size of a hot spot, detection requires a relatively small instantaneous field of view (IFOV) combined with sensitivity. The sensor must detect a small hot spot (e.g., 1-square-foot hot spot at 600° C) at altitudes of 10,000 feet. Hot spots of very high temperature are distinguished from warm terrain features by their spectral characteristics. A threshold (or a system of multiple thresholds) is implemented at a standardized output signal level. Signals above the established threshold standard are considered fire targets.

Both fire detection and mapping missions are accomplished at a variety of aircraft altitudes and speeds. The extreme requirement on sensor V/H comes from the low-altitude mapping mission, at 2000 feet altitude and 120 knots. The scanner V/H is sufficient to allow for 50% overlap on successive scans, which

TABLE 6: POTENTIAL MID-LEVEL IR SENSOR REQUIREMENTS

Field of View	>80 degrees cross track
Detector IFOV	$\leq 2.5$ mrad
Spectral Bands	3-4.8 $\mu\text{m}$ (Channel A) 8.5-12.5 $\mu\text{m}$ (Channel B)
Sensitivity	$\leq 0.2$ K (Both Bands)
Maximum V/H (velocity to height ratio)	$\geq .21$ radians/second

allows double detection of small fires for rejection of spurious noise spikes. The scanner V/H is sufficient to meet the requirements over the range of operational aircraft conditions. A comprehensive map could be achieved with the line scanner system at low altitudes in addition to the mid-level altitudes.

The commercial availability and the modular design of the mid-level sensor system would make it ideal for mapping missions other than fire. Additional band detectors could be incorporated into the system to detect vegetational stress due to disease, pest infestations, and/or drought. With the appropriate selected detectors the system would be capable of monitoring and mapping fuels for fire prevention planning over large geographical areas.

### 5.2.3 High-Level Sensor

The high-level sensor would be restricted by the availability of commercial satellite system data chosen for the production of the image data. The high-level sensor would be useful in providing the "big picture" information. The spectral and spatial characteristics of the NOAA series satellite sensors (Advanced Very High Resolution Radiometer) are well documented (Matson, 1984). The polar-orbiting, NOAA series of environmental satellites provides one visible band, one near-infrared band, and three thermal infrared bands for twice-daily, day-night monitoring of the Earth's surface. The swath width of a typical satellite image is 2600 kilometers with latitudinal coverage of about 15 degrees. The best spatial resolution of each channel is 1.1 kilometers.

Because of the altitude of the satellites it is difficult to achieve a high spatial resolution. Either more detectors are required in the instrument focal plane, or more highly powered optics are needed, each of these adding considerable cost and technological uncertainty. The non-military systems product would



have a spatial resolution that would not provide detail on individual fires but would be helpful in providing the "large picture" at a regional or statewide basis.

Multiple sensor systems, depending upon actual requirements, could be available on the NASA/AMES ER-2. The sensor systems would provide data in the infrared as well as visible regions. The total area coverage would be dependent upon the total field of view of the selected sensor. The sensor selected would need to be resolved prior to the mission to assure the availability of equipment and support processing when required. The large picture product could be provided by the ER-2 system after post-flight processing of the sensor output data.

#### 5.2.4 Spot Sensors

Hand-held non-imaging sensors could be used along a fire line or in a structure to detect hot spots. Spot sensors will detect temperature intensity which would not be detected by the eye during mop-up operations or heavily smoke-obscured conditions. These sensors are inexpensive and easy to use but also have the lowest performance of the infrared sensors.

#### 5.2.5 Fixed Position Sensor Systems

Fixed position sensor systems can be included in the concept system configuration to enable the near real-time detection of fires within the geographical range of such systems. Fixed position sensor systems have the advantage of automatic remote detection capabilities with the understanding of the inherent limiting characteristics of the system. Fixed position sensors are limited to the line-of-sight of the system and the detection sensitivity range of the sensor. Prior knowledge of the radiating profile (radiant sources such as lumber mills, refuse dumps, etc.) of the observable landscape would need to be programmed into the data base of the fixed position system. The need for a large number of these systems because of line-of-sight limitations and the large diverse geographical area in California would require a large capital investment. The requirements for an additional communication system and data processing facility would increase system costs.

### 5.3 COMMUNICATIONS

Communications technologies for temporary remote fixed service, remote portable and mobile service, and aeronautical mobile communications are

progressing rapidly. Advanced modulation techniques are using less spectrum per channel, thereby increasing the number of channels available. Specialized satellite services are being developed allowing ubiquitous mobile and portable communications for land vehicles and aircraft. Very Large Scale Integration (VLSI) chip technology is reducing the size of communications equipment while making it more reliable with greater capability. There is a multitude of potential applications of communications technologies to the concept system configuration for wildland fire mapping and detection. Commercially available communications equipment to meet the needs of the concept system configuration are summarized in the Technology Evaluation Matrix (Figure 8).

Technologies exist for transportable earth stations providing interconnect via satellite with the public-switched telephone network. Land and aeronautical mobile radio communications capability is well developed, but only for relatively short-range (line-of-sight with repeater) applications. Ubiquitous coverage for airborne and terrestrial mobiles will require satellite service, which currently exists only for limited experimental applications. Current CDF communications links could be utilized to support an infrared system.

The communications portion of the concept system configuration has elements of current technologies at both ends of the telemetry link. The system elements consist of telemetry modems, transceivers and radios. The communications interface will be a standard serial computer port to eliminate the need for manual operation. The standard interface will allow automatic data transmission and error checking when radio frequency line-of-sight conditions exist between segments.

### 5.3.1 Remote Site Fixed Communications

Telephone and data circuits can be made available to any remote location in the United States using current fixed communication satellite technology. The relatively heavy and bulky earth station antennas required for use with current communications satellites can be hauled via truck/trailer to the remote site. The earth stations can be installed and operating at a site a few hours after arrival of the equipment. Complete end-to-end service is available commercially on a contractual basis.

Transportable earth stations for fixed service will continue to be available in the 1990s. Technology advancements in earth station antenna design will result in much more lightweight and durable equipment in the future.

TECHNOLOGY CRITERIA	REMOTE SITE FIXED COMMUNICATIONS	AERONAUTICAL AND LAND MOBILE COMMUNICATIONS
COST	<ul style="list-style-type: none"> <li>• Set up charge : \$1400 plus mileage</li> <li>• Weekly rate for terminal: \$1000</li> <li>• Satellite transponder: \$0.70 /minute</li> <li>• Telephone interconnect: As billed by vendor</li> <li>• Power conditioner: \$70 installation charge, \$66/month</li> <li>• Data link: separate charge TBD</li> </ul>	<ul style="list-style-type: none"> <li>• Terminals: Approximately \$3000</li> <li>• Per minute: \$0.15 to \$0.80</li> <li>• Other charges: TBD</li> </ul>
AVAILABILITY	<ul style="list-style-type: none"> <li>• Currently available</li> </ul>	<ul style="list-style-type: none"> <li>• Not currently available</li> <li>• Projected availability: Mid to late 1990's</li> </ul>
TIMELINESS OF TRANSMISSION	<ul style="list-style-type: none"> <li>• Similar to current telephone and data satellite links (little delay). Dependent on grade of service.</li> </ul>	<ul style="list-style-type: none"> <li>• Little or no delay in transmission</li> </ul>
PHYSICAL SIZE AND POWER	<ul style="list-style-type: none"> <li>• Large, heavy antennas, not easily transported</li> </ul>	<ul style="list-style-type: none"> <li>• Mobile radios: comparable to current cellular systems</li> <li>• Small, lightweight vehicle rooftop antennas</li> </ul>
RELIABILITY, MAINTAINABILITY	<ul style="list-style-type: none"> <li>• Very reliable</li> <li>• Requires specialized maintenance</li> </ul>	<ul style="list-style-type: none"> <li>• Projected to be similar to current mobile radio equipment</li> </ul>
OTHER	<ul style="list-style-type: none"> <li>• Not applicable</li> </ul>	<ul style="list-style-type: none"> <li>• Will depend on FCC frequency allocation and licensing TBD</li> </ul>

Figure 8. Technology Evaluation Matrix: communications.

The commercially available equipment will provide timely transmission dependent upon grade or quality of service selected and the number of channels used (all are dependent on costs). Commercially provided fixed remote service is generally backed by technical crews and 24-hour service centers, although these resources may not be located close enough to the fire base camp to be useful in coping with an emergency breakdown. Many companies market a variety of earth station antennas designed to withstand environmental extremes (such as extreme cold).

### 5.3.2 Aeronautical and Land Mobile Communications

Radio communications technology exists today and is well established for air-to-ground and ground-to-air applications for localized areas. However, ubiquitous, long-range coverage (such as an aircraft in Southern California transmitting to Sacramento) currently does not exist. Long-range coverage is feasible using mobile satellite communications technology, and frequency allocations existing in L-band for aeronautical mobile satellite service.

Land mobile radio communications are well developed today and are available within the CDF. Applications are mainly for line-of-sight with repeaters (generally urban areas with large numbers of users, and localized rural areas). Existing 9600-channel packet radios use established communications techniques and provide standard computer and radio interfaces for flexibility. Current voice grade, VHF low-band radios and packet controllers have been demonstrated operationally in remote sites, but are currently transmission-limited to 1200 bits per second.

Cost-effective, ubiquitous coverage for land and air mobile radios in remote areas will require communications via satellite. The technology is feasible today but exists for limited experimental applications only. The mobile satellite communications will be similar to those available today but will have nationwide instead of localized coverage. The reliability, maintainability and durability will be the same as for cellular radio equipment. Little or no delay in voice communications or data transmission will occur as it will be comparable to current telephone service. The mobile radio will be comparable to current units that are located in the passenger compartment or mounted on the trunk. The antennas will be small and light enough to be carried on the rooftop of a car or truck. The mobile satellite communications system will be available in the mid-1990s.

## 5.4 DATA PROCESSING

The data-processing portion of the concept system configuration processes, displays, and produces hard copy of the fire data, and is the operator interface with the system. Both onboard and ground processing is accomplished within this configuration. The basis for the data-processing system is the ability to interface with the InciNet ground data system under joint development of the Forest Service and CDF.

### 5.4.1 Onboard Data Processing

A variety of functions may be performed with onboard processing. The most significant problem affecting aircraft-gathered imagery is that of geometric distortion. The majority of the distortion can be attributed to aircraft movement during image acquisition. Additional sources of distortion are extreme viewing angles of the sensor and terrain variations which result in non-orthogonal images. A second major problem in acquiring imagery from a moving aircraft is the difficulty in maintaining geographic reference. Inertial Navigation equipment, GPS receivers, and digital terrain elevation models can be used to determine the location of a particular point on the ground accurately enough for fire management needs. Current advanced computer chips are capable of processing large amounts of information in real time or near-real time. Significant onboard processing is necessary when using imaging instruments to reduce the data volume that must be transferred to the ground-processing facility and/or the fire incident base.

The onboard data processor accepts the tagged fire and hot spot data from the sensor system and generates graphical data sets in order to compute the ground position of each fire data point in a georeferencing process. The primary purpose of the georeference software is to compensate for avionics errors (pitch, roll, yaw) at the higher altitudes, and topographic relief displacement at the lower altitudes. Topographic relief displacement is the shift in observed position of an object due to the elevation (topographic relief) of that object relative to the base elevation (datum). Georeferencing entails the calculation of the latitude and longitude coordinates of fire perimeter and hot spot information recorded by the sensor, for transmission to the incident base system (InciNet) for accurate overlay and plotting upon United States Geological Survey (USGS) quadrangle maps.

The data-processing system corrects for topographic relief displacement with a typical maximum error of less than two meters RMS, and ten meters RMS error under sub-optimal conditions. Avionic errors (pitch, roll and heading) increase with aircraft altitude, and are less than 73m RMS at 4572m above base elevation under the worst possible conditions. The combined worst case situation (at 5-meter pixel resolution) with maximum avionics errors, and relief displacement of 800m, is 77m RMS at 4572m above base elevation, and 30m RMS at 1524m. The approach exceeds 100-meter RMS accuracy when the aircraft is below 5486m (18,000ft) above base elevation.

The basic need for the georeferencing includes 1) real-time processing in less than 30 minutes after image acquisition; 2) positional accuracy within 100 meters RMS (300 ft); and 3) a coverage rate greater than 400 square miles per hour.

The software would require a 2 MIPS (million instructions per second) CPU to process within the required time period. Conventional microcomputers (e.g., Macintosh II; IBM PC-AT) average a 2 MIPS CPU. The proposed baseline hardware configuration for data processing, therefore, would utilize a ruggedized microcomputer (e.g., Macintosh II). Ruggedized microcomputers are readily available (e.g., Greensprings Inc., Atlantic Research Corporation). These systems can also be configured with a ruggedized 60+MB hard disk system, which is greater than is needed for storing flight data plus operating system and scratch space.

#### 5.4.2 Ground Processing

The ground processing of fire data could be done simultaneously at the Incident Base, region office, and central facility (location could be Sacramento) after transmission from the sensor platform. The ground-processing facility will be the automated information system (InciNet) currently under development by the CDF and the Forest Service under a cooperative agreement. The InciNet system will be developed for use at fire and other disaster sites. InciNet is defined as a standardized, interagency on-scene system which provides automated data processing and a data communications system which allows both internal and external information sharing.

To take advantage of archival and existing data bases regarding wildland attributes, a variety of the following processing steps may be done at the InciNet ground facility.

- Display of fire data onto standard USGS topographic maps at any desired scale,
- Cost/benefit analysis regarding the impending economic loss or advantage could be outlined in a map or graphic form for easy reading,
- Incorporation of fuel type maps, when available, to assist the fire managers with suppression and management,
- Fuel moisture display from timely meteorological data across a pre-defined grid,
- Use of computer rate-of-spread models to predict fire behavior.

A simulation of the output of the concept system configuration is illustrated in Figure 9. The fire data, at four ranges of intensity, is plotted to scale on a standard topographic map base. The 50-meter fire data cells are positioned within 300 feet of the actual ground location at the time of data collection. A system operator on board the aircraft has provided ancillary information on roads and streams. The data collection was no more than 30 minutes prior to the time it was received by the fire manager.

## 5.5 ECONOMIC ANALYSIS OF CONCEPT SYSTEM CONFIGURATION

Potential economic impacts of the concept system configuration were identified in a study (Appendix C) conducted by personnel from the CDF (Jim Spero, Economic Analyst, CDF Fire Protection Planning Staff) and University of California, Berkeley (Dr. J. Keith Gilles, Professor of Forest Economics). Interviews were conducted with incident commanders and/or operations section chiefs from several recent major fires to determine if investment in IR technology by the CDF was economically justified. The interviews covered both the deployment and use of ground resources (engines, dozers, and handcrews) and air operations (helicopters and fixed-wing aircraft).

The consensus of those interviewed was that total resource usage to contain the fire incidents considered would not have changed as a result of having IR intelligence. Once the fires were contained, however, the incident commanders were in agreement that improved IR intelligence would result in significant savings in the duration of mop-up operations. Estimates of this time savings ranged from 20% to 50%. Budgetary savings and reduced property losses are likely because of: (1) fewer resources used in mop-up due to more efficient resources usage and less time devoted to mop-up operations; and (2) reductions in structure damage due to improved fire fighting efficiency.

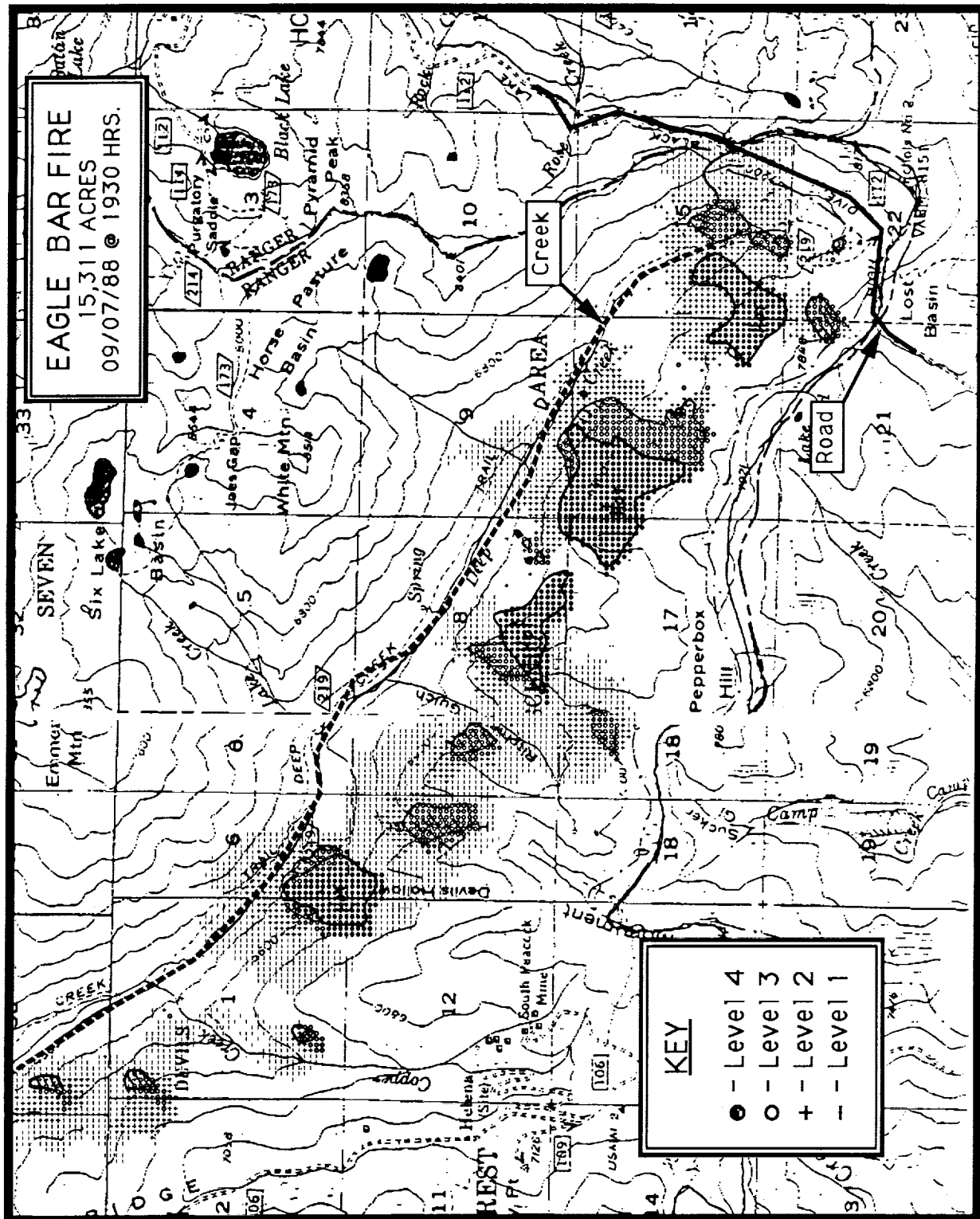


Figure 9. Simulated output.



The interviewees were in general consensus that at least a 5% reduction in numbers of structures lost would be a conservative estimate of the impact of improved IR intelligence. A 5% reduction in property damage would benefit the public by reducing public and private losses by more than \$1.1 million dollars annually, or \$9.2 million (1988 dollars) per decade.

Depending on the density of vegetation fuel loading, savings in mop-up time would range from 20% to 50%. This would result in at least an annual savings of \$.7 million, or \$5.6 million (1988 dollars) over a decade in emergency fund expenditures.

Increased efficiency of air operations (effective placement of retardant drops, rapid location of spot fires to assist in reducing fire size) could result from improved IR capabilities. Although the study concluded that the economic impact or magnitude of this benefit from IR is not amenable to estimation, a small increase in the efficiency in this area would yield important savings of the \$7 million in annual air operations expenditures.

On the basis of the interviews, it is clear that significant savings in expenditures on both ground resources and air operations could be achieved with improved IR capability, particularly in mop-up operations. Further, significant reductions in property damage on major fires could be realized from improved IR intelligence.



## SECTION 6

### CONCEPTUAL DESIGN

The conceptual design phase should be the next phase in the development of an infrared system to meet the fire information needs of the CDF. The conceptual design phase is intended to define and select the system which warrants continued development, to identify major uncertainties (with recommendations for resolution during subsequent design phases), to determine operational capability and characteristics, to provide preliminary costs and schedule estimates, and to examine cost/benefits ratios.

The beginning of the conceptual design phase is concerned primarily with the translation of user needs into a quantifiable set of functional requirements that can be translated into design requirements. Needs expressed by users in the field are first formulated as a set of objectives and identified as a set of project goals. The objectives are quantified in broad terms, and basic functions are identified that could fulfill the need. The requirements (performance, operational, environmental, documentation, safety, etc.) are identified and expressed in measurable parameters which state user needs in terms that technologists can use to develop system concepts. This process is an iterative operation, constantly refining and identifying new requirements as the concept develops and additional details are defined. As a result of analysis of the requirements, a set of candidate system designs is formulated and evaluated in terms of performance, cost, and schedule. While this process ideally results in an optimum technical system, in actuality there are limitations on cost, schedule and risk which place constraints on system design. The result is the selection of a preferred system from a number of candidates, rather than the optimum technical solution.

#### 6.1 GOALS

The goals of the conceptual phase will be to develop the concept for a total system. The total system would include the multi-level platforms and sensor systems, communication links, the processing and georeferencing of the data, and the data display for the end user. The various elements and functions of that system will be reviewed and projections of technology availability made for each. Risk areas and unknowns will be identified. Alternative approaches will be discussed. Real requirements would be understood, and a plan to meet

requirements within an agreed set of constraints and resources would be documented during this phase. At the conclusion of the conceptual phase, a viable approach for subsequent development phases will be documented.

More specifically, the following questions should be addressed during the conceptual design phase:

1. How can the system be modularized to minimize obsolescence and retain capability to use newly developed equipment?
2. What image/digital processing functions can reasonably be done aboard the aircraft and which should be done at a central facility and/or mobile command post unit?
3. What are the specifications of the final products needed by the fire manager or other users?
4. Can the system be made versatile enough for multiple uses (e.g., insect and disease management, mapping, etc.), through interchangeability of sensor front-ends or multiple band sensors?
5. How can the system provide inputs to existing/developing computer models or utilize existing/developing data bases?
6. What are the milestones, decision points, and general schedule for the succeeding implementation phases?
7. What additional technologies will be available in the early 1990s that would enhance an infrared system, and which should be considered for application?
8. What are the communication needs and what methods and systems should be used?
9. What contributions (fiscal, technical) could be made by additional State of California agencies?
10. What institutional (regulatory, political) issues may be encountered?
11. What system design is recommended for further development?
12. What type and how many aircraft will be needed/available to support a multi-level infrared system?
13. How should a system phase-in be scheduled?
14. What are the cost/benefit ratios associated with the preferred system configuration?

## 6.2 DESIGN TEAM

A design team for the conceptual design phase would be assembled. The design team would consist of California Department of Forestry and Fire

Protection personnel and members of the Jet Propulsion Laboratory technical staff. CDF management will provide guidance and direction. JPL personnel will provide the specialized expertise in the variety of technical disciplines explored and developed in this report. The team would consult with various CDF region personnel from time to time to obtain user guidance and prepare reports as needed.

### 6.3 DESIGN IMPLEMENTATION

The conceptual design phase would conclude with the evaluation and recommendation of a preferred system configuration for development in a subsequent design implementation phase. The design implementation phase activities would include obtaining the resources necessary to do the job, designing the final system, reviewing the activities, and delivering the system to the sponsor.



## SECTION 7

### CONCLUSION

Planning for the arrival of new technology and the application of existing technology has its obvious advantages. If a planning effort is undertaken that anticipates future technological developments, then the planning process has a head start and is less susceptible to obsolescence. When new developments mature, they can be accommodated more quickly, completely, and conveniently.

Existing and future infrared technologies promise solutions to fire management information needs unique to the State of California. The geography of California is extensive and varied, and protecting the state's wildland resources from fire poses a unique set of challenges. Existing and emerging infrared technologies afford promising solutions to a variety of the state's fire management information needs. The concept system configuration presented in this report is a viable solution for information needs for the State of California.

The professional landscape of California is as varied as the geography. There are experts in fire management and experts in advanced technologies. So far there has been only limited interaction of these two groups of experts, but even this limited interaction has inspired the development of important fire management tools. With current expertise at hand and the benefit of past experience both in fire management and advanced technology, further work in this area is strongly recommended.





## REFERENCES

Colwell, R. N., Manual of Remote Sensing, American Society of Photogrammetry, Falls Church, VA, 1983.

Enmark, H., Fire Logistics Airborne Mapping Equipment (FLAME) Final Report (JPL Internal Document) Jet Propulsion Laboratory, Pasadena, CA, April 23, 1984.

Hirsch, S. N., et al., Project FIRESCAN Fire Mapping Final Report, Research Paper INT-49, USDA, Forest Service, Washington, D. C., 1968.

Hudson, R. D., Jr., Infrared System Engineering, J. Wiley & Sons, New York, NY, 1969.

Lloyd, J. M., Thermal Imaging Systems, Plenum Press, New York, NY, 1975.

Nichols, J. D., et al., "Designing an Infrared System To Map and Detect Wildland Fires," Sensor Fusion II, Charles B. Weaver, Editor, Proceedings SPIE 1100, pp. 7-15, 1989.

Maston, M., et al., Fire Detection Using the NOAA-Series Satellites, NOAA Technical Report NESDIS 7, USDC, National Oceanic and Atmospheric Administration, Washington, D. C., January 1984.

Weaver, R., Forward Looking Infrared System (FLIR), California Department of Forestry and Fire Protection, Sacramento, CA, June 1983.

Weaver, R., California's 1987 Lightning Fire Outbreak. Remote Sensing Information at the State Level, Unpublished Report, California Department of Forestry and Fire Protection, Sacramento, CA, January 5, 1988.



## APPENDIX A

### CDF Regional Personnel Interviewees

## CDF Regional Personnel Interviewees

### NAME

### TITLE

#### REGION I - SANTA ROSA

Steve H. Hubbard	SFRI	Humboldt, RU
Don Rominger	Dep. Chief Air Ops	SAC HQ
Gene Whitten	ECC Chief	Humboldt RU
Del Walters	Battalion Chief	Sonoma RU
Tom Osipowich	Forester II	Region I HQ
Gil Werder	SFR II	Region I VMP
Jim Gahagan	SFR II	Sonoma RU
Jeff Hawkins	SFR I	Region I HQ
Ron W. Thomas	Fire Captain	Sonoma RU

#### REGION II - REDDING

Reid Stenbach	Air Attack Officer	Shasta-Trinity RU
Carl Wolf	Division Chief (planning)	Valley View CC
Bob Brown	Forester II (safety officer)	Region II HQ
Bruce Young	Division Chief (planning)	Sugar Pine CC
Royal Burnett	Battalion Chief OPS FBA	Shasta-Trinity RU
Dennis Bebensee	Forester II	Tehama-Glenn RU
Mike Terwilliger	Battalion Chief (operations)	Tehama-Glen RU
Frank Goddard	Forester	Lassen-Modoc RU
Dave Garcia	Civil Engineer	Redding Region II HQ
Bill Hoehman	Dep. Chief	Redding-Siskiyou RU
Craig Carter	VMP Cord.	Butte RU

#### REGION III - RIVERSIDE

Kevin Eggleston	Field Bat. Chief	San Bernardino RU
Chuck Maner	Field Bat. Chief	San Diego RU
Eric Oldar	Forester (IR interpreter)	RO III HQ, Riverside
Bob Robeson	Div. Chief	San Diego, Morena C.C.
Steve Heil	Div. Chief	Ventura C.C.
Cliff Dulcich	Div. Chief	Fenner Cyn C.C.
Mike Warren	Forester II VMP	San Bernardino RU
Ken Sigsbee	Div. Chief	Riverside RU
Mike Harris	Dep. Chief	Region III HQ
John Timmer	Div. Chief (operations)	San Bernardino RU

## REGION IV - FRESNO

Norm Cook  
Bill Schultz  
Brian Weatherford

Res. Manager  
Div. Chief  
Dep. Chief

Fresno Region IV HQ  
Tuolumne-Calaveras RU  
Fresno Region IV HQ



## APPENDIX B

### Summary of Discussions with CDF Regional Personnel

August 24-25, September 15, 21, 1989

Summary of Discussions with CDF  
Regional Personnel  
August 24-25, September 15, 21, 1989

- CURRENT USE/ AVAILABILITY OF INFRARED (IR) EQUIPMENT
  - IR equipment is not available much of time, especially U.S. Forest Service line scanner
  - Type of IR equipment that will be sent to fire is unknown until it arrives
  - Experience with IR varies greatly
  - Training on IR is not current
  - Capability of current IR systems is not known (what specific systems can and cannot do and how they should be used)
  - IR data is currently not timely in use with initial attack or extended attack
  - When line scanner data is available there are questions as to the accuracy of the data
  - Getting any IR data within 12 hours of fire start is a big problem
  - People trained to operate and interpret IR are not always available
- USER NEEDS FOR INFRARED - FIRE
  - Mapping of fire lines with indication of fire intensity
  - Tactically need information on where fire is instantaneously, to the meter level
  - Strategically need information on the entire fire, in 6 to 24 hours, to  $\pm 500$  feet
  - Synoptic view of region of interest, within a week, to  $\pm 1^\circ$
  - Need knowledge of current fire conditions
  - Need information on where fire is in timely manner
  - Where fire is going
  - How well suppression activities are doing
  - Spotting and intensity of fire
  - Detection of fires especially after dry lightning storms
  - At Fire Operations, Chief will use IR differently than Plans Chief
  - Re-evaluation of fire after suppression
  - Evaluation of air tanker drops
  - Documentation for post-fire lawsuits



- USER NEEDS FOR INFRARED - MULTIPLE USES
  - Vegetation management tool - fuel loading, die back, etc.
  - Mapping pest infestations
  - Mapping of vegetation stress - disease identification
  - Monitoring prescribed burning
  - Surveillance for law enforcement activities
  - Data base layer for statewide Geographical Information System
  - Contract IR services to other state agencies
  
- USE OF IR IN INITIAL ATTACK - WITHIN FIRST HOUR
  - Initial attack Incident Commander needs to find where fire is and where it is going, as soon as possible after fire start
  - Air attack aircraft would be good platform for FLIR System to provide early fire information
  - IR could be provided to Incident Commander as video image and/or quick look snapshot or initial small fire
  - IR necessary in real time in initial attack
  - Variable field of view would be beneficial
  - FLIR or Probeye IR Systems difficult to use from helicopter
  - IR in air attack fixed-wing aircraft is good platform to evaluate efficiency of air tanker drops
  
- USE OF IR IN EXTENDED OR MAJOR FIRE SITUATION
  - Initial attack Incident Commander needs to find where fire is and where it is going, as soon as possible after fire start
  - Air attack aircraft would be good platform for FLIR System to provide early fire information
  - IR could be provided to Incident Commander as video image and/or quick look snapshot or initial attack
  - IR necessary in real time in initial attack
  - Variable field of view would be beneficial
  - FLIR or Probeye IR Systems difficult to use from helicopter
  - IR in air attack fixed-wing aircraft is good platform to evaluate efficiency of air tanker drops

- USE OF IR IN EXTENDED OR MAJOR FIRE SITUATION
  - Mid-level platform with line scanner would provide information on entire fire
  - Information would include fire perimeter, hot spots, indication of fire intensity
  - Would be available anywhere in California within 12 hours
  - Information would be available to the Incident Commander in near real time (within 30 minutes of data collection)
  - Repeat coverage would be available for each new planning meeting
  - Map output products important
  - Map products used would be easy to duplicate
  - Information would be transmitted to fire camps, regional offices, Sacramento if needed
  - FLIR Systems could be used tactically on specific fire line or sector
  
- MANAGEMENT ISSUES
  - Priority of where IR incorporated into operational use
  - Phased approach to determine what use is most important
  - Coordination with aircraft capabilities, availability, and competing aircraft use
  - Training program
  - Cost/benefits trade-offs analysis
  - IR program would eventually need manager with support staff

## **APPENDIX C**

### **Potential Cost Savings from CDF Use of Infrared Technologies for Wildland Fire Suppression and Management**

## Potential Cost Savings from CDF Use of Infrared Technologies for Wildland Fire Suppression and Management

### Executive Summary

The California Department of Forestry and Fire Protection (CDF) has contracted with the National Aeronautics and Space Administration's Jet Propulsion Laboratory (JPL) to prepare a feasibility study on the potential use of advanced infrared technology by CDF. As part of that study, Jim Spero (Economic Analyst, CDF Fire Protection Planning staff) and Dr. J. Keith Gilles (Professor of Forest Economics, University of California at Berkeley) conducted expert opinion interviews with incident commanders and/or operations section chiefs from several recent major fires to determine if investment in IR technology by the CDF was economically justified.

The interviews covered both the deployment and use of ground resources; such as, engines, dozers, and handcrews (Part 1 of this report) and air operations (helicopters and fixed-wing aircraft - Part 2). On the basis of these interviews, it is clear that significant savings in expenditures on both ground resources and air operations could be achieved with improved IR capability, particularly in mop-up operations. Further, significant reductions in property damage on major fires could be realized from improved IR intelligence.

This study did not consider the high-level IR platform (either satellite or pressurized aircraft). This kind of intelligence is generally of more use to Sacramento Headquarters in making strategic planning decisions in times of widespread fire occurrence. We feel the high-level platform could have economic benefits, although probably too diffuse to measure.

## PART 1 - GROUND RESOURCES

### 1.1 Interview Format

The interviews were conducted in June, 1990, and followed a common format:

a. The elements of the proposed IR system were described; i.e., the capabilities and specifications were discussed for the proposed:

- i) high-level (satellite),
- ii) mid-level (IR dual band line scanner), and
- iii) low-level (airborne FLIR) systems.

b. Using incident maps and photographs, the CDF personnel were asked to give a detailed chronological history of the fire.

c. The CDF personnel were then asked to identify all times/situations in the course of the fire at which a lack of intelligence of the sort provided by some element of the proposed IR system was in some sense limiting.

d. The times/situations thus identified, were then discussed in detail with respect to how the IR intelligence might have affected the way in which the fire was fought and how the potential outcome might have been different (e.g., fewer acres or homes burned).

e. The CDF personnel were then asked to identify the numbers and types of firefighting resources employed on the fire (if this had not previously been discussed as part of steps b or d). Their recollections were confirmed using CDF records (ICS 209, FC 40, or FC 18 forms).

f. The ways in which this resource usage might have been different with complete IR intelligence were then discussed in detail. While the discussion was allowed to follow a fairly natural flow, the interviewers were consistent in making sure that potential changes in resource usage was explicitly considered in terms of numbers/percentages needed in the interval from fire start to containment to the end of operations. Engine, dozer, handcrew, and aircraft usage was discussed in both separate and collective terms.

g. Finally, the issue of uncertainty was addressed in terms of whether or not some numbers of resources were "held" to provide a margin of safety for gaps in intelligence at any point in the course of fighting the fire in question.

Rather than rely on a formal survey questionnaire, the interviewers minimized note-taking during discussions, but taped the interviews to provide a record for later review. This procedure seemed effective in creating a relaxed and candid atmosphere for discussion.

## 1.2 Incidents Considered

Identification of the fires for which expert interviews would be conducted started from the list of Class "D" and larger fires (i.e., all 100 plus-acre fires) which occurred in 1987 and 1988 since the bulk of CDF emergency fund expenditures occurs on fires in these size classes. Incidents from this list for which incident maps and FC 40 cost reports could be located were then identified. Operations section chiefs or incident commanders from these fires were then identified and contacted to set up interviews. Through this process, expert-opinion interviews were ultimately conducted for a total of six fires, two from CDF Region I (North Coast), three from Region II (Sierra Cascade) and one from Region III (Southern California):

<u>Incident</u>	<u>CDF Acres burned</u>	<u>Date</u>
Mendenhall	14,080	9/2/87
Lauder	1,400	9/29/87
49er	33,700	9/11/88
Fern	7,790	9/17/88
Powderhouse	200	8/26/88
Palomar	6,440	10/03/87

## 1.3 Interview Results

The consensus of those interviewed was that total resource usage to contain these fires would not have changed as a result of having the IR intelligence for a variety of reasons. In the 49er and Fern fires, in particular, the rationale for this conclusion was the need to protect structures and improvements, and the tremendous drain this places on resources.

Once the fires were contained, however, the incident commanders were in agreement that improved IR intelligence would result in significant savings in the duration of mop-up operations. Estimates of this time savings ranged from 20% to 50%. While some reduction in the quantities of resources devoted to mop-up was anticipated by the incident commanders, this savings was considered to be of minor importance relative to the overall time savings realizable from more effective deployment. It was clear that achieving such savings, however, would require an integrated utilization of the mid-level and low-level IR systems.

The range in estimated savings in mop-up operations was directly correlated with fuel loading; i.e., the greatest saving would be realized in heavy timber fuels, less in brush/woodlands, and the least in grass fuels.

The incident commanders interviewed were also emphatic that with IR intelligence of the sort provided by the proposed system, their efforts to be proactive in defending values at risk would have been

more effective. Considering both the specific fires identified above, and experiences on other large incidents, the interviewees were in general consensus that at least a 5% reduction in numbers of structures lost would be a conservative estimate of the impact of improved IR intelligence.

#### 1.4 Economic Findings: Use of IR in Ground Operations is Economically Justified

The middle- and low-level IR configurations proposed by JPL are economically justifiable investments for the CDF. Budgetary savings and reduced property losses are likely because of: (1) fewer resources used in mop-up due to more efficient resource usage and less time devoted to mop-up operations; and (2) reductions in structure damage due to improved firefighting efficiency.

##### a. Reduced damage to property

A 5% reduction in property damage would benefit the public by reducing public and private losses by more than \$1.1 million dollars annually, or \$9.2 million (1988) dollars per decade. According to CDF records<sup>1</sup> damage to dwellings and other structures caused by wildland fires in California were as follows:

STATE RESPONSIBILITY -- CDF DIRECT PROTECTION  
APPX. DOLLAR DAMAGE - ALL REGIONS  
(in 1988 dollars<sup>2</sup>)

Year	1984	1985	1986	1987	1988
No. of Class D & Larger Fires	115	127	88	93	132
Dwellings	10,159,339	18,605,831	8,326,350		
Structures	2,005,809	6,193,289	3,871,598	28,457,569 <sup>3</sup>	36,730,968
Total	12,165,148	24,799,120	12,197,948	28,457,569	36,730,968
Per Fire(Divide By No. of Fires)	/115	/127	/88	/93	/132
	105,784	195,269	138,613	305,995	278,265

o Per Fire Five Year Average Dwelling and Structure Damage = 204,785

o Estimated Total Annual Dwelling and Structure Damage based on Average Number of Class D and Larger Fires which occurred during the Past Five Years = \$22,731,135

1. Wildfire Activity Statistics CDF publication [yearly, 1984 through 1988].

2. Adjustment by Consumer Price Index.

3. The 1987 and 1988 editions of the Redbook combined dwellings and structures in a summary category.

Using the estimated \$22,731,135 in yearly losses from property damage by fire, a 5 percent reduction resulting from use of IR by CDF would mean an economic benefit to property owners of \$1,136,557 per year in avoided damages. These benefits would accumulate throughout the life of the investment.

Assuming a 10-year service life and a (real) discount rate of 4%, ignoring salvage value, tax considerations or operating/maintenance costs, the present value of the stream of benefits to property owners would be \$9,217,477.

b. Depending on the density of vegetation fuel loading, savings in mop-up time would range from 20-50%. This would result in at least an annual savings of \$.7 million, or \$5.6 million (1988 dollars) over a decade in emergency fund expenditures.

Although CDF's mop-up costs are not reported directly, they can be roughly estimated. U.S. Forest Service researchers used data on hours spent by fire crews in mop-up operations on nine National Forests in the Western United States to develop a regression model to predict mop-up costs.<sup>1</sup> They concluded that:

... mopup costs are high when compared with cost estimates of other fire management activities or with total cost of extinguishing a fire.

and also that:

Mopup costs in the Lolo National Forest...are 39 percent of the total average suppression cost.

The USFS estimate of 39% is probably high for much of the land under CDF protection. Land under CDF direct protection is covered, generally, by lighter fuels than are found on the Lolo National Forest. However, the greater threat of property damage on land under CDF protection causes CDF fire managers to be highly risk averse, leading to more careful mop-up as a form of insurance. A very conservative estimate, therefore, of the percentage of total costs on large fires attributable to mop-up operations would be 20%.

We used this 20% figure to estimate the portion of emergency fund expenditures that would be subject to savings from shorter mop-up

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1. Gonzales-Caban, Armando Costs of Firefighting Mopup Activities, US Dept. of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley: California (Research Note PSW-367 - August 1984).



times. Only two cost categories from the emergency fund were most likely to include significant mop-up costs: overtime and contract labor. These costs were averaged, and a savings of 20% was calculated assuming costs would go down by the same percentage as mop-up time.

CDF's emergency fire suppression expenditures for unplanned overtime and for contract labor are directly related to mop-up activities. Handcrews provide much of the labor; such as, by mixing dirt into burning fuels, breaking up concentrations of fuels, and patrolling the fireline. Engines and bulldozers are used in mop-up operations; however, aircraft and contracted equipment are used far less frequently if at all.

Although other expenditure categories clearly contain significant expenditures from mop-up operations, we did not include vehicle operations, subsistence, consultant & professional services, utilities, facilities operation, travel, communication, general expenses and emergency employee costs in the calculations below. Considering only employee overtime and contract labor, CDF emergency fund expenditures for the last three fire seasons were:

DEPARTMENT OF FORESTRY AND FIRE PROTECTION  
Emergency Fire Suppression Expenditures  
(\$ in Thousands - 1988 constant dollars)<sup>1</sup>

Items	1986-87	1987-88	1988-89 <sup>2</sup>
Employee Overtime	3,089	14,093	13,624 (approx.)
Contract Labor	2,485	8,873	9,366 (approx.)
	<u>6,019</u>	<u>23,923</u>	<u>22,990</u>

Simple average = \$17,176,666

x .20 = \$3,435,333 (Average Mop Up Cost per Year)

Therefore, yearly mop-up cost savings are estimated at:

$$.20 \times \$3,435,333 = \$687,066$$

Using the same discounting procedure as before (4% for 10 years) we determine the present value of the savings over one decade in mop-up costs resulting from the proposed investment in IR systems as \$5,572,111.

1. Cost data obtained from the Department's CALSTARS reports and adjusted by Consumer Price Index.

2. Estimated YTD as of August 15, 1989 (CDF Budget Office).

## PART 2 - AIR OPERATIONS

### 2.1 Recent Research on Airborne FLIR

The Operational Retardant Evaluation (ORE) study sponsored by the USFS had as an objective for 1989 to "Evaluate/validate the usefulness of FLIR imagery in real-time by the air attack supervisor in operational situations."<sup>1</sup>

Although the ORE study cataloged about 2000 hours of recorded video and FLIR imagery, it did not address the question of how FLIR use might affect the total amount of retardant dropped by the CDF over a fire season, or how total fire losses might change from more effective use of a given annual expenditure on retardant drops.

### 2.2 Interviews Conducted

Dr. Gillless interviewed several experienced air operations supervisors regarding the potential for savings from more accurate water and retardant drops. The interview technique was similar to that used to survey ground resource use (Part 1 of this report), with the exception that no single fire was used to provide context for the discussion. The interviewees were asked to consider a wide range of possible scenarios to identify where IR would cause a reduction in per-fire retardant use due to (1) more accurate drops, or (2) quicker containment/mop-up.

### 2.3 Interview Results

From these interviews and the discussions with incident commanders outlined above, it was not possible to establish that a reduction in retardant usage would result from improved IR intelligence. It was clear that the experts interviewed saw the proposed IR systems as valuable for increasing the efficiency with which air operations were conducted, however. While more effective placement of drops and rapid location of spot fires would unquestionably assist in reducing fire size on many incidents, the economic impact or magnitude of this benefit from IR is not amenable to estimation.

### 2.4 Economic Findings

Over the last three years, the CDF averaged about \$7 million in annual expenditures on air operations. Of this figure, approximately \$3 million was for chemical retardants. A small increase in efficiency in this area would yield important savings.

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1. Memorandum from Fred A. Fuchs, Assistant Director, Fire and Aviation Management, USFS Operational Retardant Evaluation (ORE) Study Review.

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16. Abstract The National Aeronautics and Space Administration's Jet Propulsion Laboratory has completed a feasibility study using infrared technologies for wildland fire suppression and management. Sponsored by the Department of Forestry and Fire Protection, State of California, the study surveyed user needs, examined available technologies, matched the user needs with technologies, and defined an integrated infrared wildland fire-mapping concept system configuration. System component trade-offs were presented for evaluation in the concept system configuration. The economic benefits of using infrared technologies in fire suppression and management were examined. Follow-on concept system configuration development and implementation were proposed.			
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